Search for Vector-Like Quarks with ATLAS

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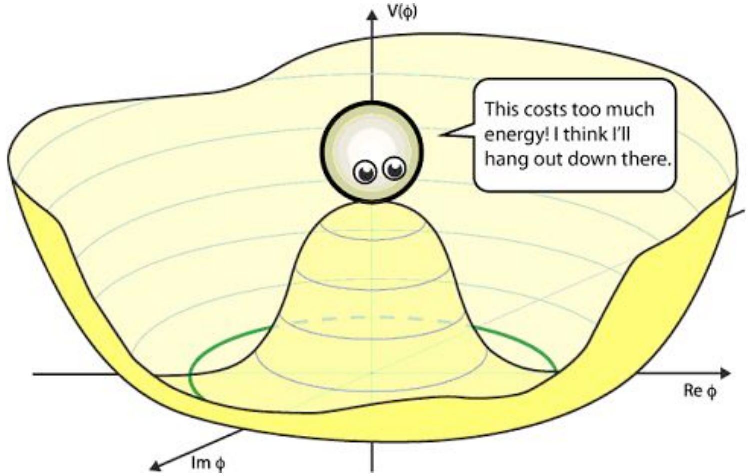
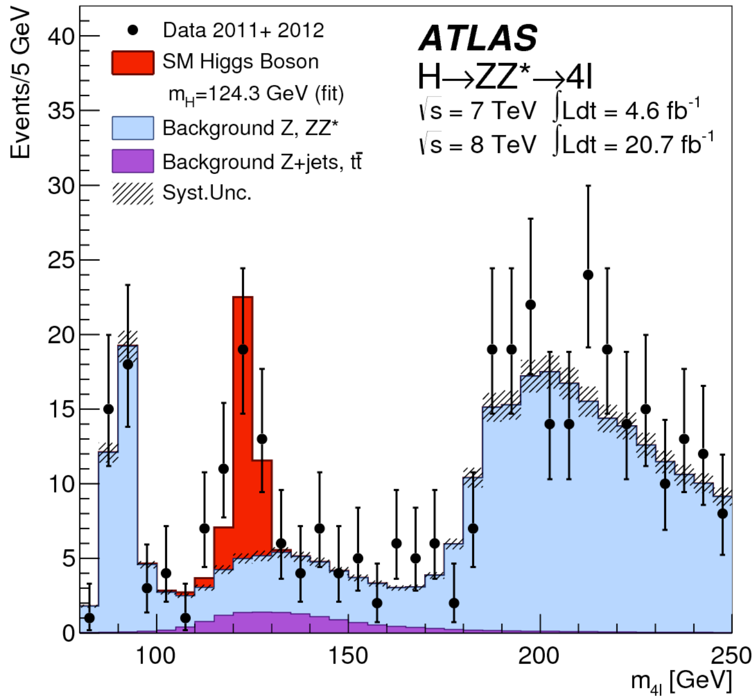
Higgs Boson



- In the Standard Model (SM), elementary particles get a mass by interacting with the Higgs field

- The SM matter particles are chiral so an explicit mass term is forbidden by the SM gauge symmetry

- Are there other forms of matter?



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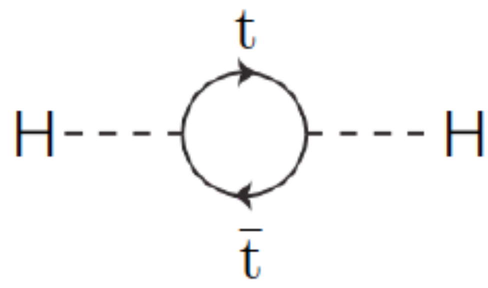
Context: Heavy Quarks and the Naturalness problem

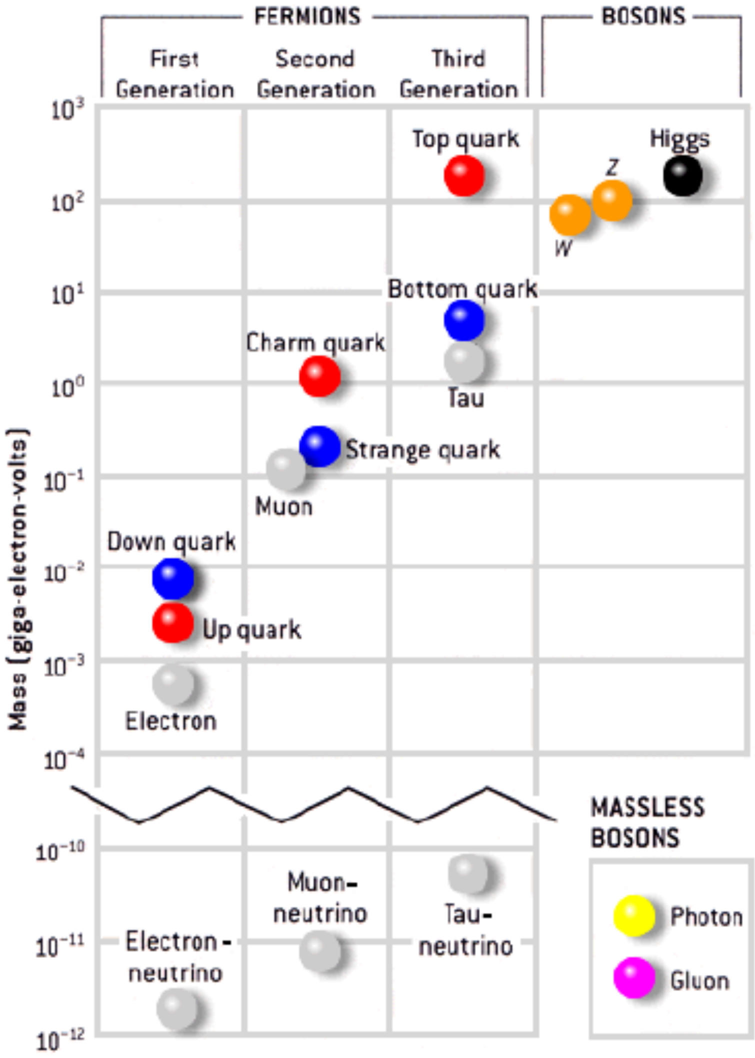
- The existence of a scalar Higgs Boson at 125 GeV is established
- Well known theoretical problem that a scalar particle has large corrections to its mass from loop corrections
- Is there a principle , symmetry, and/or new particles that render it natural?



$$m^2_{phys} = m^2_{bare} + g\Lambda^2 \ll \Lambda^2$$

FINE TUNING

Heavier Generations?



- Why 3 generations?
- Mass hierarchy is accommodated by the SM but not predicted (Higgs Yukawa couplings)
- Are there more?

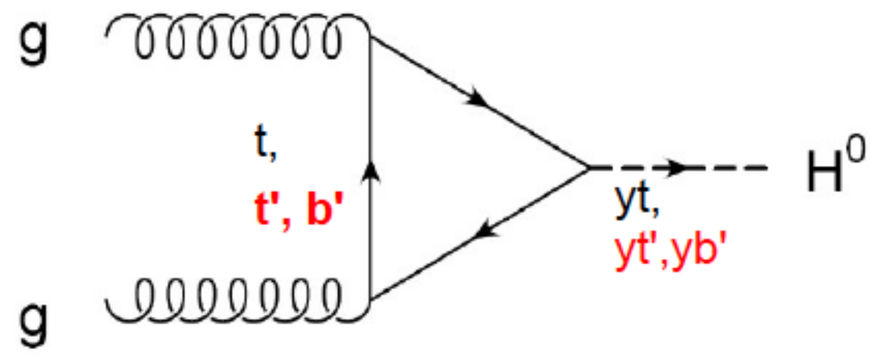
What do we know already?

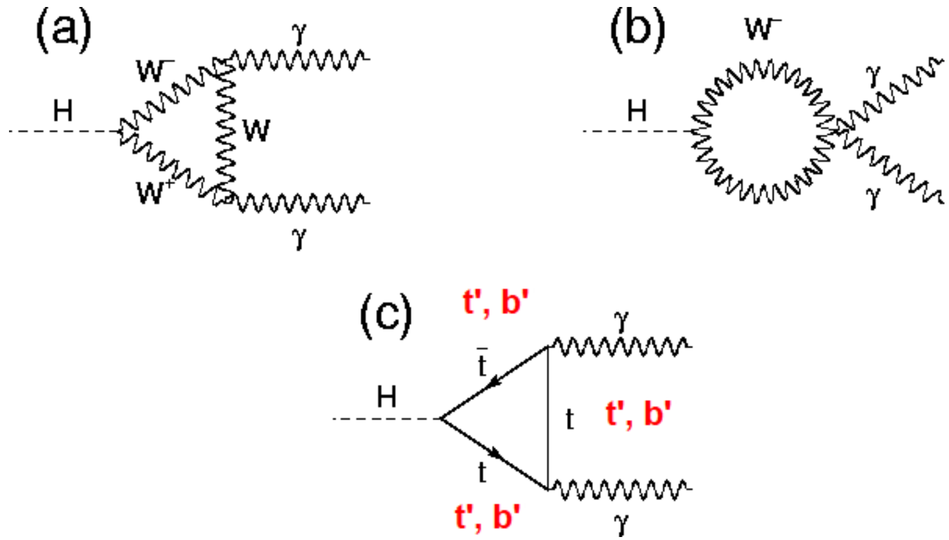
- Higgs boson measurements from the LHC strongly disfavor another chiral generation of quarks

- A new heavy chiral quark would influence Higgs production and naively increase the cross-section by ~10

- A new heavy chiral quark would influence the decay and suppress the diphoton decay by a factor of ~100

[Kuflik *et al.* , .., PRL 110 (2013)]





What is a Vector Like Quark

- Unlike SM (chiral) quarks the left and right handed fields transform the same way under SU(2)

- They have a Dirac mass without the Higgs

$$L_{mass} \sim M(\bar{\Psi}_L \Psi_R + \bar{\Psi}_R \Psi_L)$$

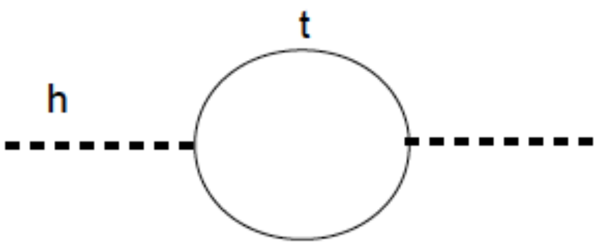
- They couple to SM quarks via Yukawa-Like interactions

$$L_{Yuk} \sim \frac{\lambda_v}{\sqrt{2}}(q_L \Psi_R + \bar{\Psi}_R q_R)$$

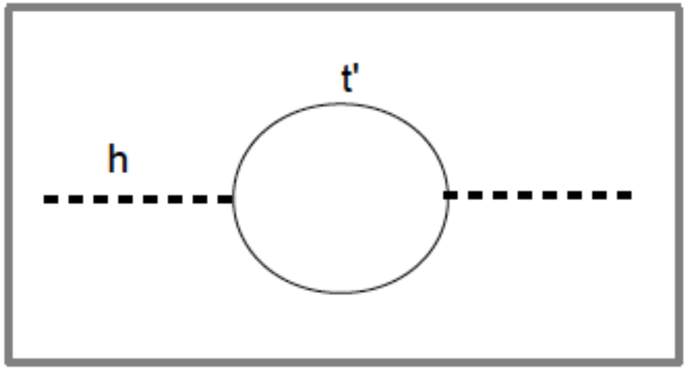
- The couplings depend upon the representation of SU(2)

    - singlet, doublet, triplet

VLQ Motivation



$$\delta m_h^2 \sim y_t^2 \Lambda^2$$

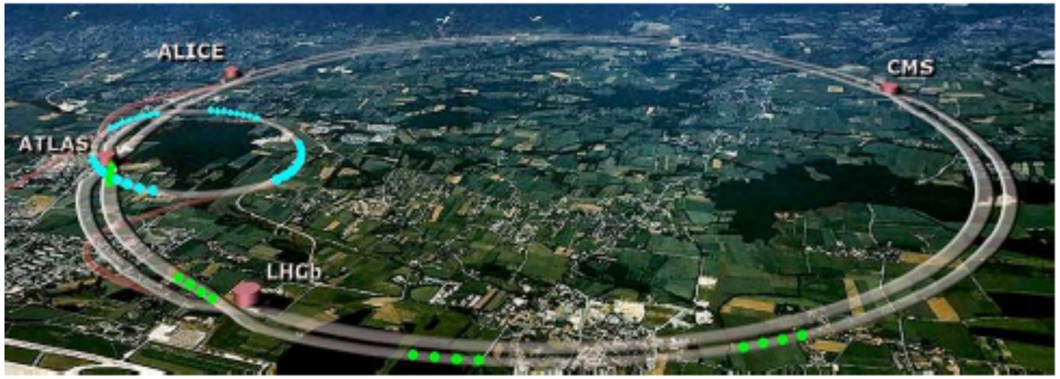


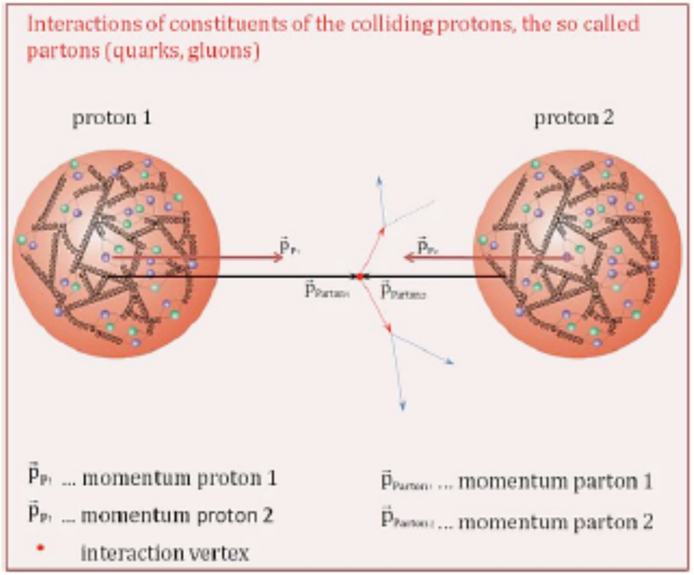
VLQ top-partners can control the Higgs mass instability

Arise in many BSM models

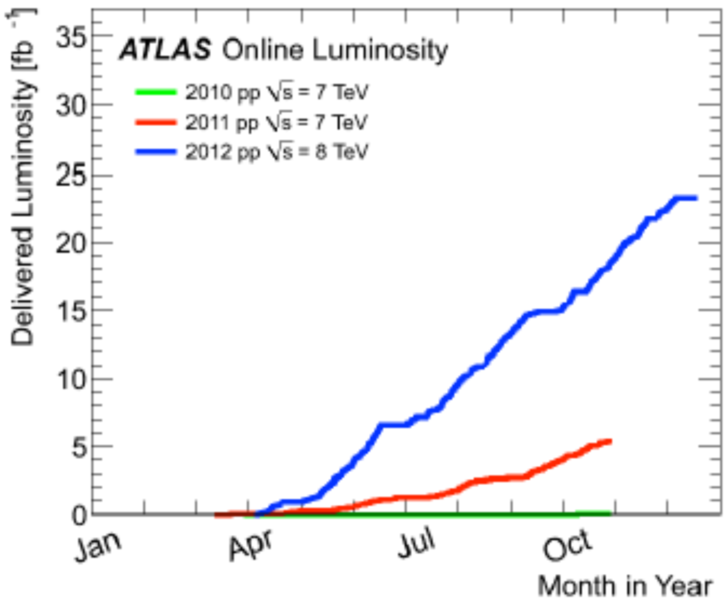
- composite Higgs
- some models SUSY
- Extra dimensions

Large Hadron Collider

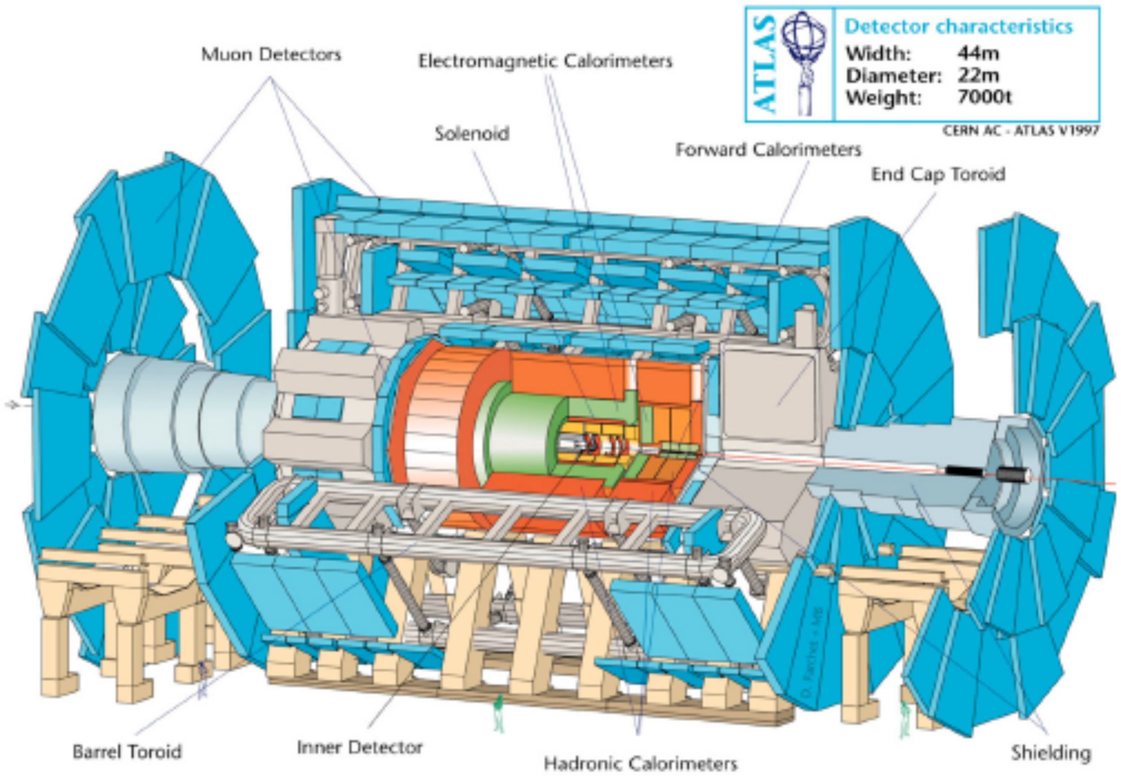




20 fb^{-1} of integrated luminosity recorded and utilized at 8 TeV

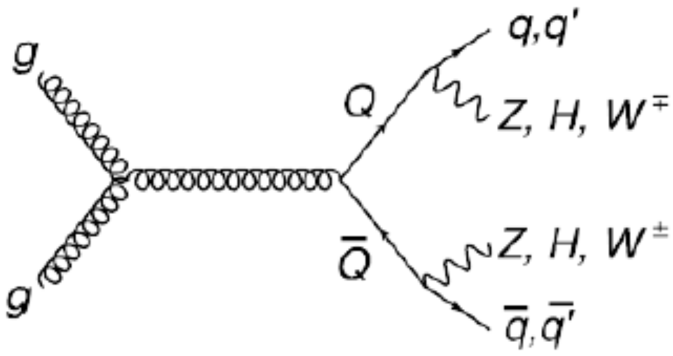


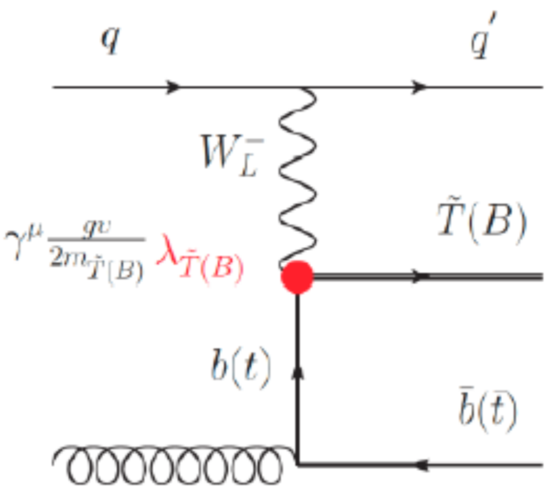
ATLAS Detector

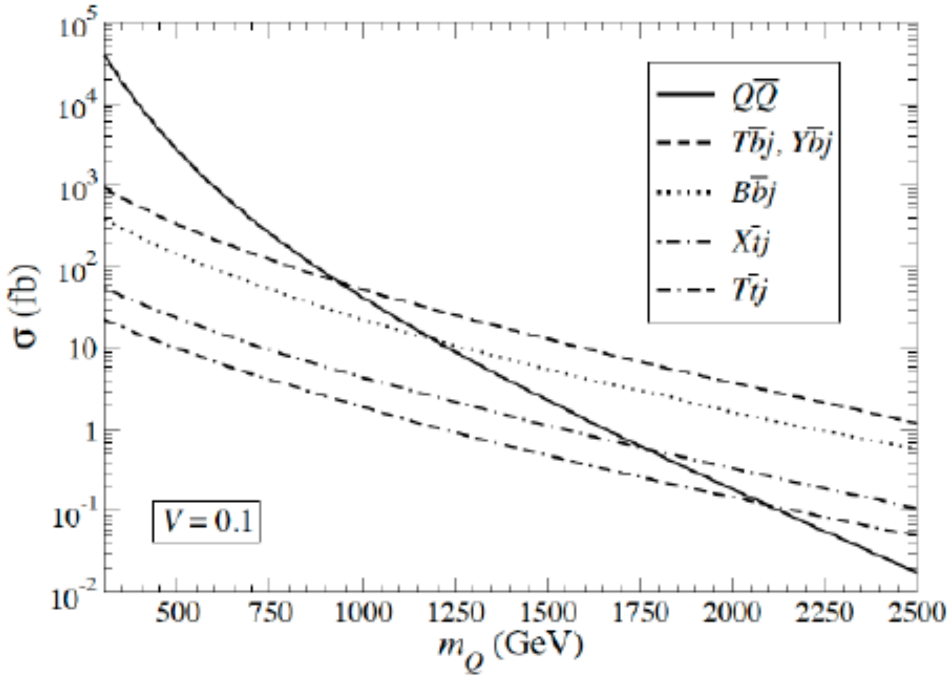


- Inner Detector (tracker) : Pixels, Silicon Strips, Transition Radiation Detector
- Calorimeters: LAr (EM + hadronic forward), TileCal (hadronic)
- Forward Detectors: LUCID< ZDZ, ALFA
- Muon Spectrometer: Drift Tubes, resistive plate chambers, thin gap chambers, and cathode strip chambers
- 4 super-conducting magnets:
  - Solenoid (ID) + 3 Toroid Magnets for Muon Spectrometer

Production



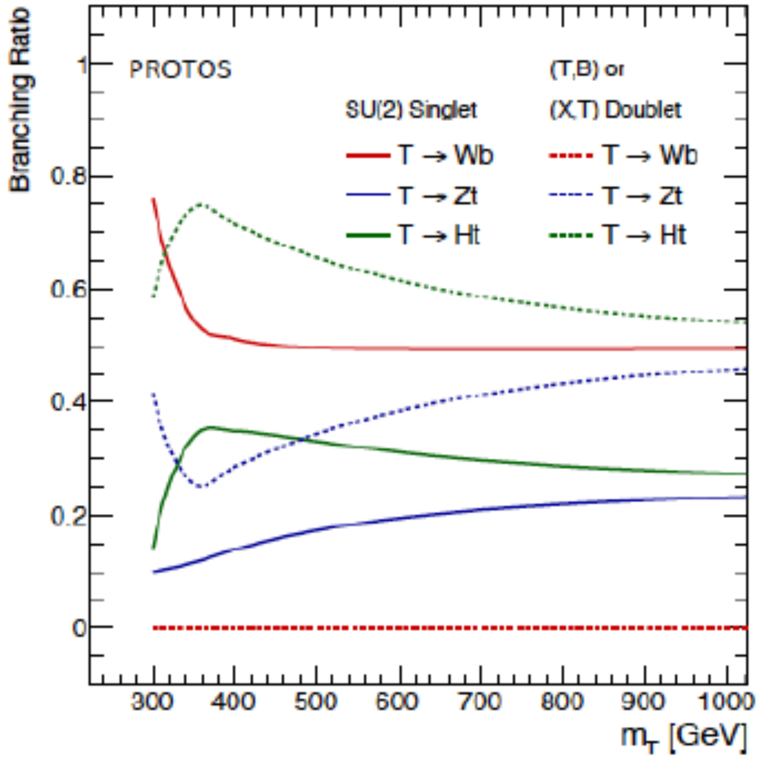




Pair or single Production

Decays

- Decays depend on assumed charge and structure (charge 2/3 or 5/3)
    - singlet, doublet, triplet
- Does not obey GIM mechanism - tree level flavor changing neutral currents



Huge Number of Final States

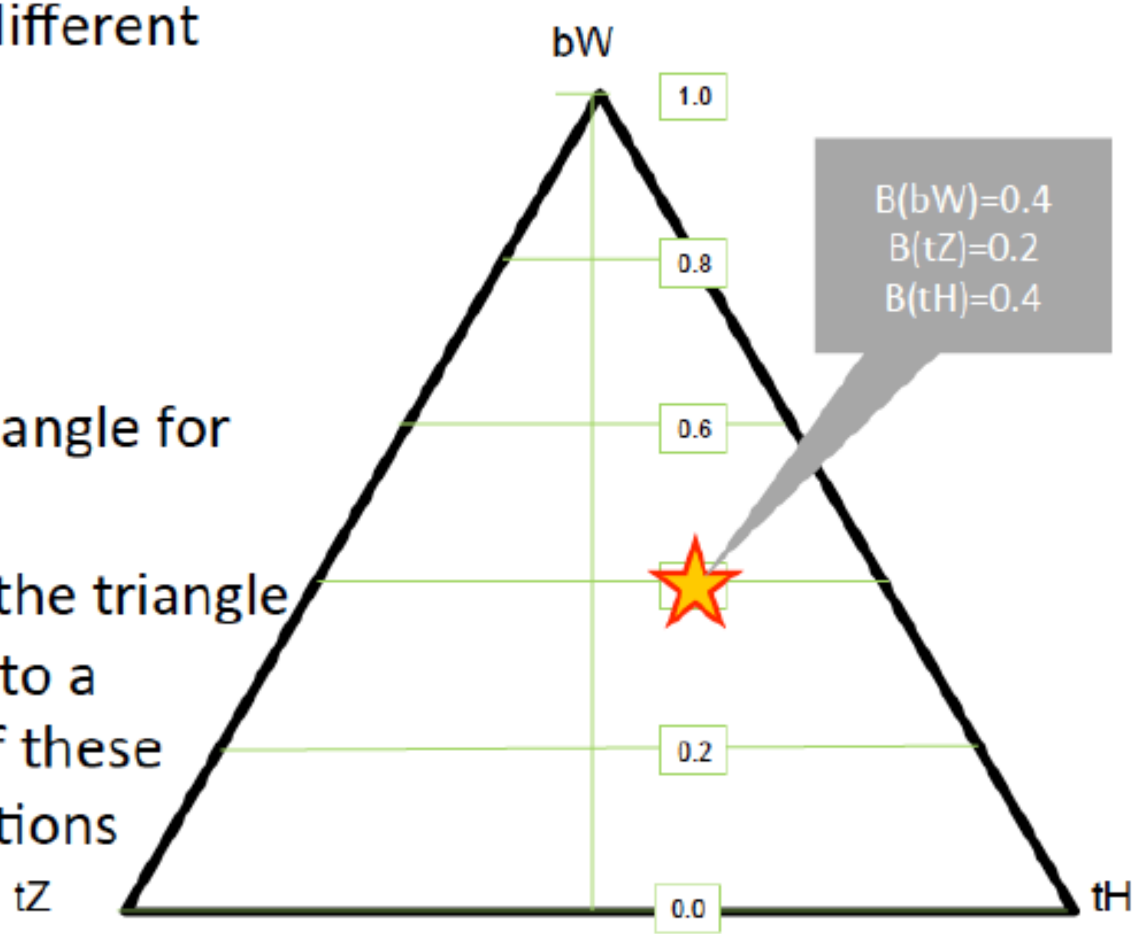
Channel	Multi-leptons	Lepton+jets
tHWb	$2l$(OS)+MET+$4b$	l+ MET+$2j$+$4b$
tH tZ ($Z \rightarrow jj(bb)$)	$2l$+MET+$2j$+$4b$	l+MET+ $4j$+$4b$
tH tZ ($Z \rightarrow \nu\nu$)	$2l$+MET+$4b$	l+ $2j$+MET+$4b$
tH tZ ($Z \rightarrow ll$)	$4l$+MET+$4b$ or $3l$+MET+$2j$+$4b$	
tZ tZ (Z$Z \rightarrow jj(bb)$)	$2l$(OS)+MET+$2j$+$2b$	l+MET+ $4j$+$2b$
tZ tZ (Z$Z \rightarrow \nu\nu$)	$2l$(OS)+MET+$2b$	l+$2j$+MET+$2b$
tZ tZ (Z$Z \rightarrow ll$)	$4l$+MET+ $2b$ or $3l$+$2j$+MET+$2b$	
tHtH ($H \rightarrow bb$)	$2l$(OS)+MET+ $6b$	l+MET+$2j$ + $6b$
WbWb	$2l$(OS)+MET+$2b$	l+MET+$2j$+$2b$
WbtZ ($Z \rightarrow jj(bb)$)	$2l$+MET+$2j$+$2b$	l+MET+$4j$+$2b$
WbtZ ($Z \rightarrow \nu\nu$)	$2l$+MET+$2b$	l+MET+$2j$+$2b$
WbtZ ($Z \rightarrow ll$)	$4l$+MET+$2b$ or $3l$+MET+$2j$+$2b$	

Channel	Multi-leptons	Lepton+jets
tHWb	$4l$+MET+$2b$ or $2l$(SS)+MET+$4j$+$2b$	l+MET+$6j$+$2b$
tH tZ ($Z \rightarrow jj(bb)$)	$4l$+MET+$2j$+$2b$ or $2l$(SS)+MET+$6j$+$2b$	l+MET+$8j$+$2b$
tH tZ ($Z \rightarrow \nu\nu$)	$4l$+MET+$2b$ or $2l$(SS)+MET+$4j$+$2b$	l+MET+$6j$+$2b$
tH tZ ($Z \rightarrow ll$)	$6l$+MET+$2b$ or $3l$+MET+$6j$+$2b$	
tHtH ($H \rightarrow W^+W^-$)	$6l$+MET+ $2b$ or $3l$+MET+$6j$+$2b$	l+MET+$10j$ + $2b$
tHtH ($H \rightarrow W^+W^-, b\bar{b}$)	$4l$+MET+ $4b$ or $2l$(SS)+MET+$4j$ + $4b$	l+MET+$6j$ + $4b$

+ Single Production Decays!

Recasting to a Triangle

- T decays into different final states
  - T→bW
  - T→tZ
  - T→tH
- there is one triangle for every T mass
- every point in the triangle corresponds to a different set of these branching fractions



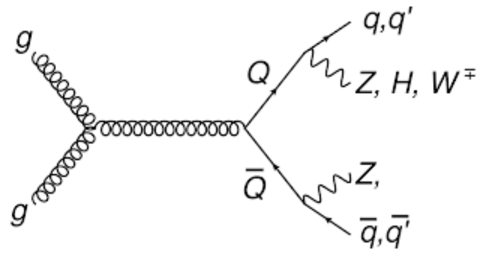
ATLAS Strategy

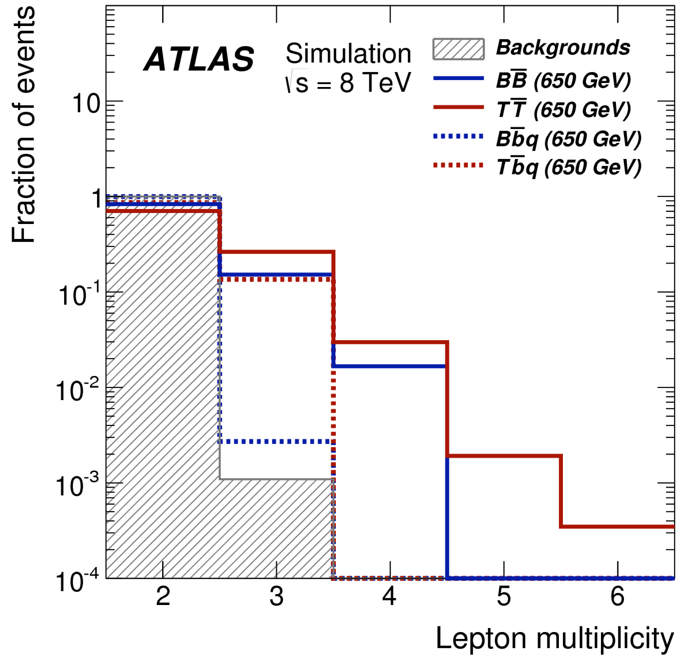
- For Run I -
    - dedicated searches in corners of decay space that are optimized for particular decays eg. tZ, tH,bW
    - Organize according to lepton multiplicity : single lepton, dilepton (divided into those with Z boson and same sign), and trilepton
    - Combine the analysis statistically for maximal coverage
- CMS type strategy - some dedicated searches and some more general inclusive searches

VLQ Analysis

- There are many searches that cover different hypothesis and final states:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
- I will mostly cover one of these in detail (that my student and I worked on) and then briefly discuss a couple of the other channels and the combination

Z-tag Analysis



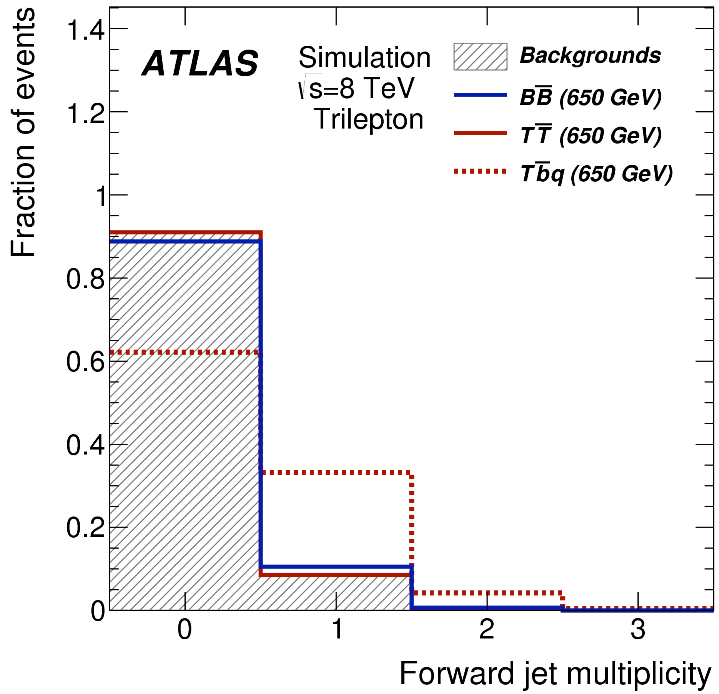


- Divide Analysis into Dilepton and Trilepton (or more) Channels

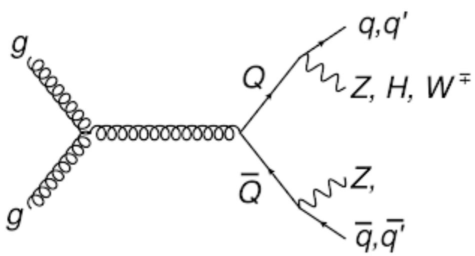
- Start by reconstructing a Z boson in the opposite sign same flavor channel

- Examine variables that are ~ model independent and give good separation between signal and background

- Some model dependence in the single production mode

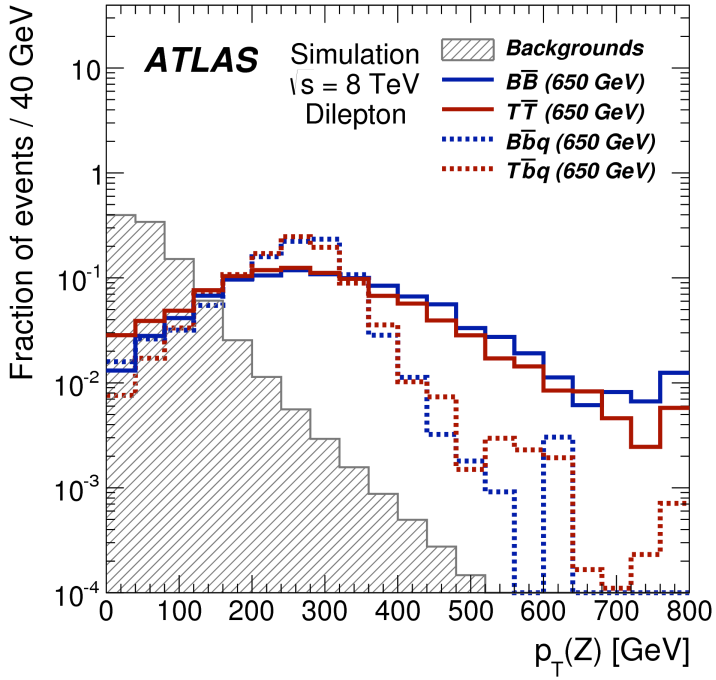


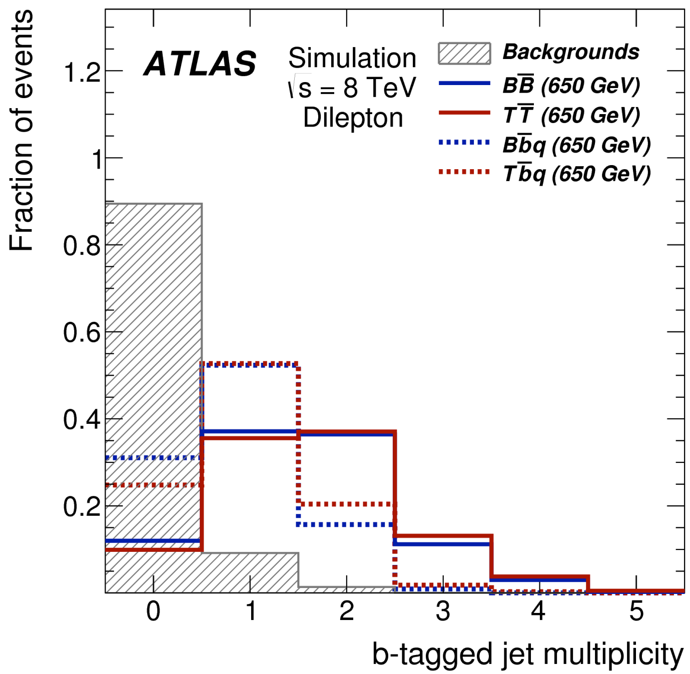
Kinematic Variables



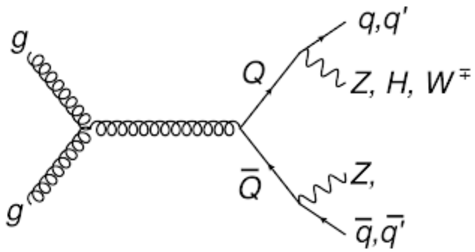
- Main background at preselection stage is Z+jets (low b-jet multiplicity and relatively low pt of Z boson)

- Signal has high Pt Z boson and multiple b-jets



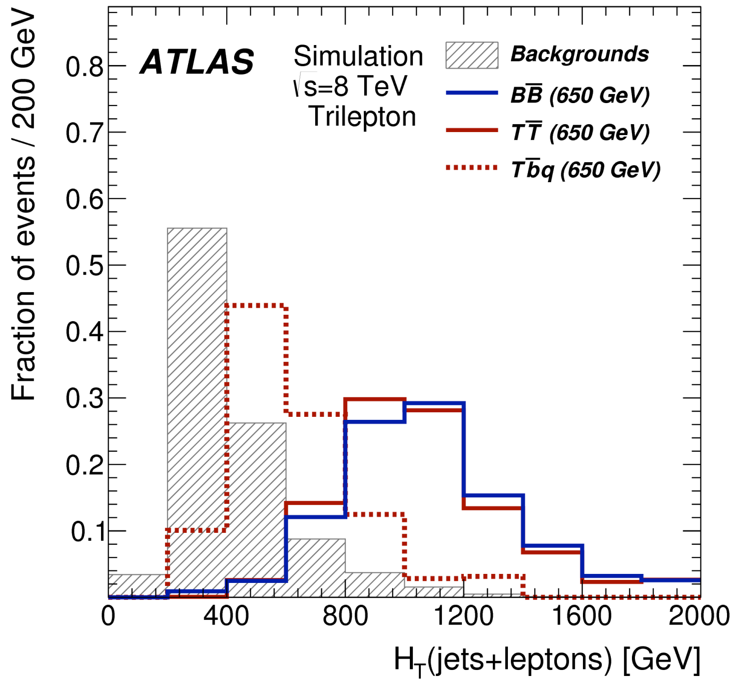


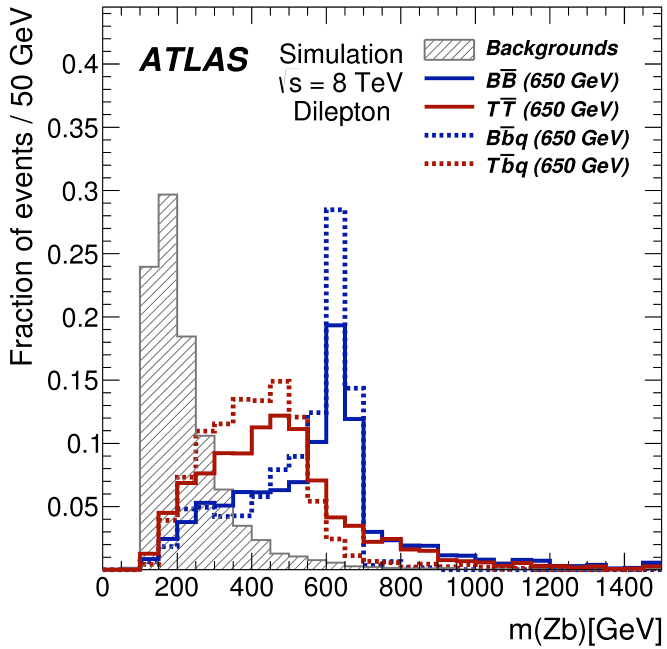
Kinematic Variables



- For heavy quark production expect in general high pt objects (as seen in the sum of all reconstructed jets and leptons)

- Invariant masses to recapture full or partial exotic quark invariant mass





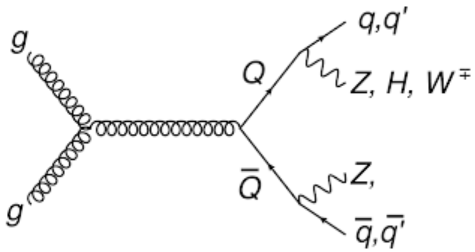
Selection Overview

<table>
<tr><th colspan="4">Event selection</th></tr>
<tr><td colspan="4">Z candidate preselection
≥ 2 central jets
$p_T(Z) \geq 150$ GeV</td></tr>
<tr><td colspan="2">Dilepton channel
$= 2$ leptons
≥ 2 b-tagged jets</td><td colspan="2">Trilepton channel
≥ 3 leptons
≥ 1 b-tagged jet</td></tr>
<tr><td>Pair production
$H_T(jets) \geq 600$ GeV</td><td>Single production
≥ 1 fwd. jet</td><td>Pair production
–</td><td>Single production
≥ 1 fwd. jet</td></tr>
<tr><th colspan="4">Final discriminant</th></tr>
<tr><td colspan="2">$m(Zb)$</td><td colspan="2">$H_T(jets + leptons)$</td></tr>
</table>

- Dilepton and Trilepton Start with Same event selection and then diverge on lepton and b-jet multiplicity

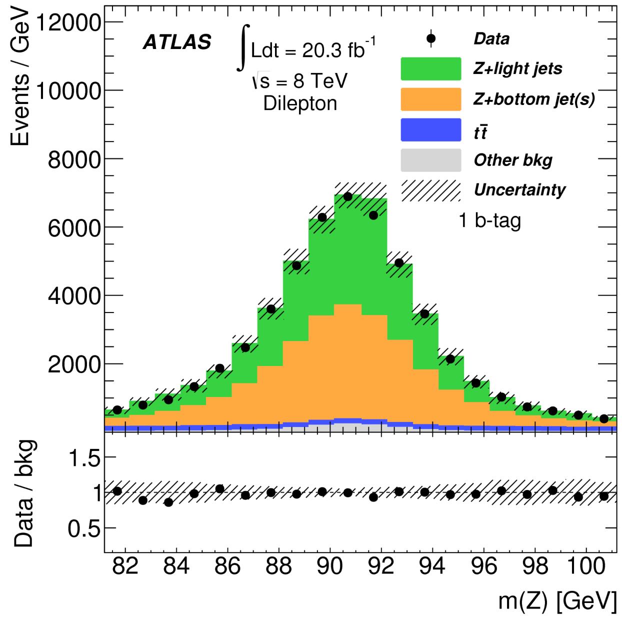
- Exploit then kinematics of process for single production (forward high energy jets)

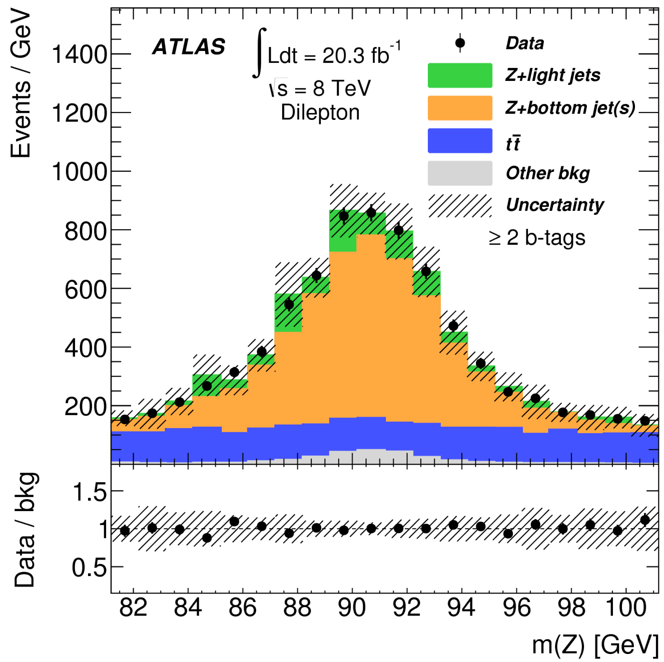
Data/MC agreement



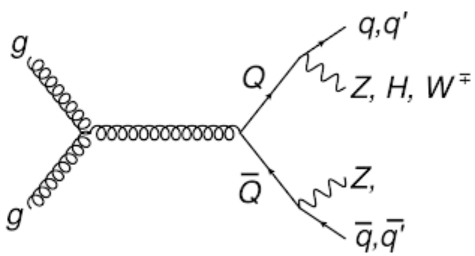
- Use the low H_T region (< 600 GeV) and Z P_T (< 150 GeV)region to compare simulation with data in a region depleted from signal

- Note change in signal composition moving from 1 to 2 b-tagged jets



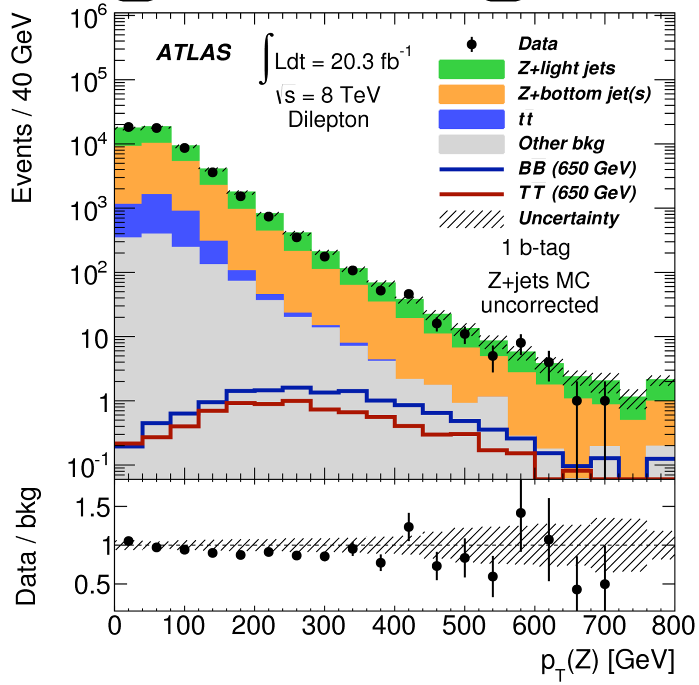


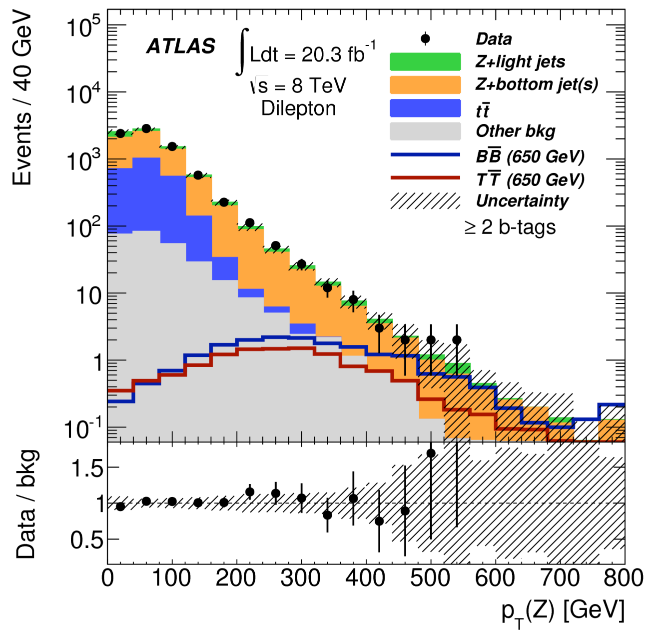
Z P_T Reweighting



- Notice a slight disagreement in out of the box agreement between Z boson transverse momentum

- Use single b-jet tag in order to derive correction for 2 b-jet tag (check 0 b-jet bin for closure)





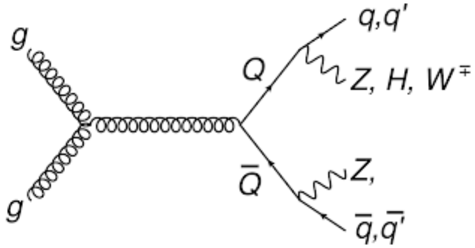
Data Driven Correction

- Two corrections made : Z+jets MC seen to under predict background in the 1,2 jet Z P_T < 150 GeV region by ~15 , 20%

	$Z+\geq 2$ jets ($N_{tag}-1$)	$p_T(Z) > 150$ GeV	H_T(jets) > 600 GeV
Z+light (no p_T corr.)	24000 ± 1500	1940 ± 190	104.6 ± 8.6
Z+light (p_T corr.)	23600 ± 1500	1700 ± 150	89 ± 12
Z+bottom (no p_T corr.)	24100 ± 1700	1970 ± 240	82.5 ± 8.0
Z+bottom (p_T corr.)	23600 ± 1700	1730 ± 160	71 ± 11
$t\bar{t}$	2850 ± 230	68 ± 11	8.0 ± 2.9
Other SM	1250 ± 370	180 ± 60	17.9 ± 5.7
Total SM (no p_T corr.)	52200 ± 2300	4150 ± 310	213 ± 13
Total SM (p_T corr.)	51300 ± 2300	3690 ± 230	186 ± 16

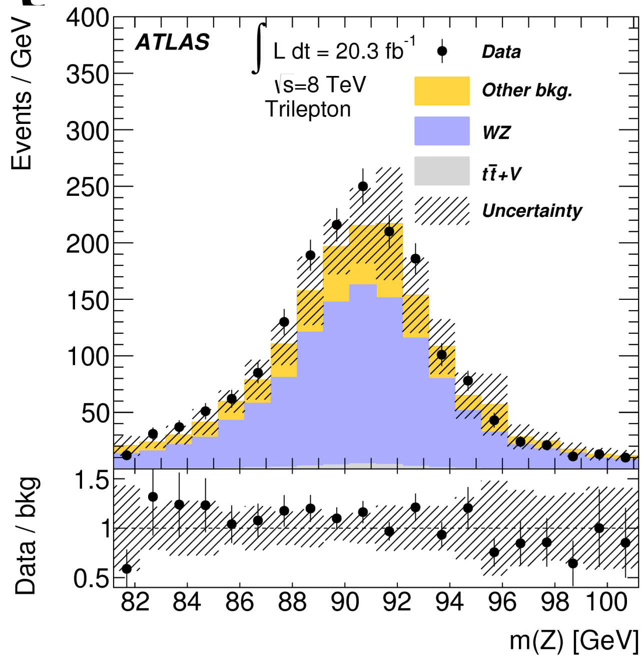
- Z pt correction ~10%

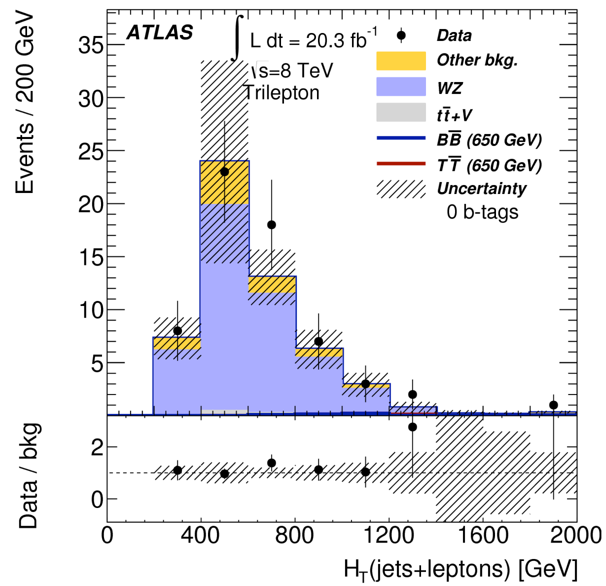
Trilepton Data/MC Agreement



- After third lepton requirement - dominated by WZ

- Apply a k-factor from NLO program (1.18) and get reasonable agreement in various kinematic variables





Systematic Errors

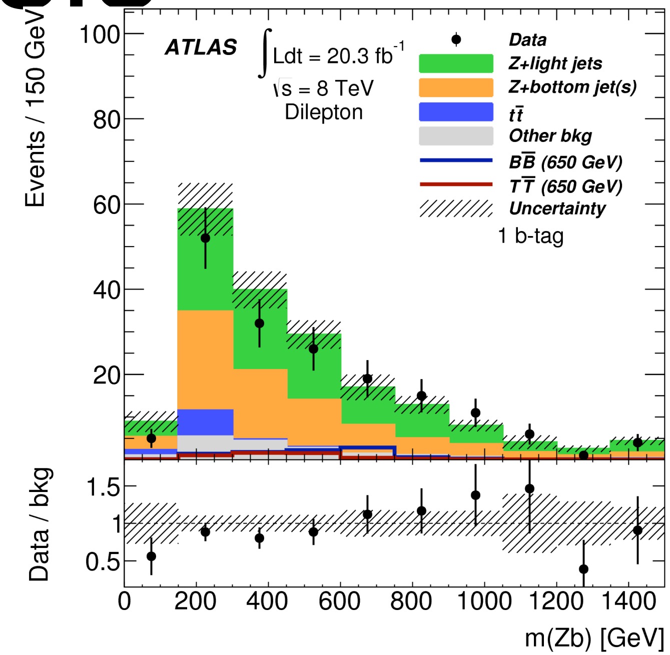
Fractional uncertainties (%): dilepton channel						
	Z+jets	$t\bar{t}$	Other bkg.	Total bkg.	$B\bar{B}$	$T\bar{T}$
Luminosity	1.4	2.8	2.8	0.3	2.8	2.8
Cross section	5.5	6.4	29	0.7	-	-
Jet reconstruction	13	10	14	11	2.0	2.1
b-tagging	9.1	13	9.9	5.7	7.2	5.9
e reconstruction	2.9	16	5.9	4.6	2.5	1.5
μ reconstruction	3.8	7.8	7.2	4.2	3.2	1.3
Z+jets $p_{\mathrm{T}}(Z)$ correction	9.0	-	-	6.5	-	-
Z+jets rate correction	6.9	-	-	5.0	-	-
MC statistics	5.0	25	12	5.4	2.4	2.9

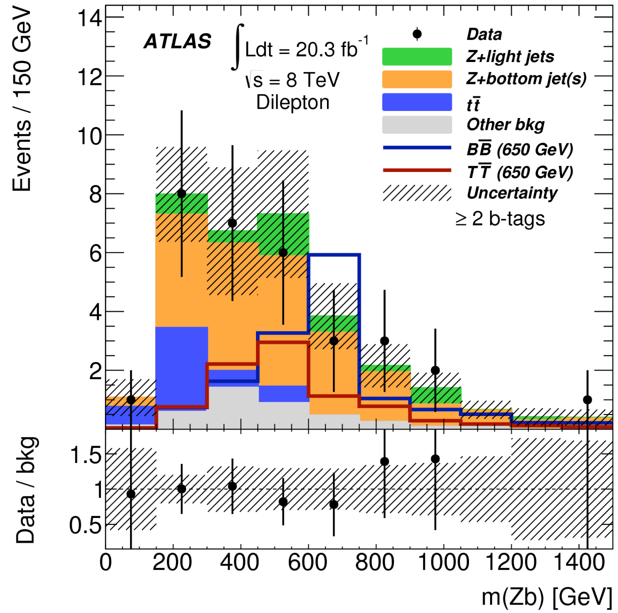
Fractional uncertainties (%): trilepton channel						
	WZ	$t\bar{t}+V$	Other bkg.	Total bkg.	$B\bar{B}$	$T\bar{T}$
Luminosity	2.8	2.8	2.8	2.8	2.8	2.8
Cross section	17	30	8.9	21	-	-
Jet reconstruction	5.4	1.2	8.1	3.1	4.0	1.8
b-tagging	13	3.6	13	6.7	5.6	5.5
e reconstruction	9.3	3.9	37	11	5.9	12
μ reconstruction	14	3.9	18	4.2	6.2	5.7
MC statistics	11	3.1	27	6.6	4.8	8.3

Final Variables in Pair Production Hypothesis

- Good agreement with data/mc in both dilepton and trilepton analysis

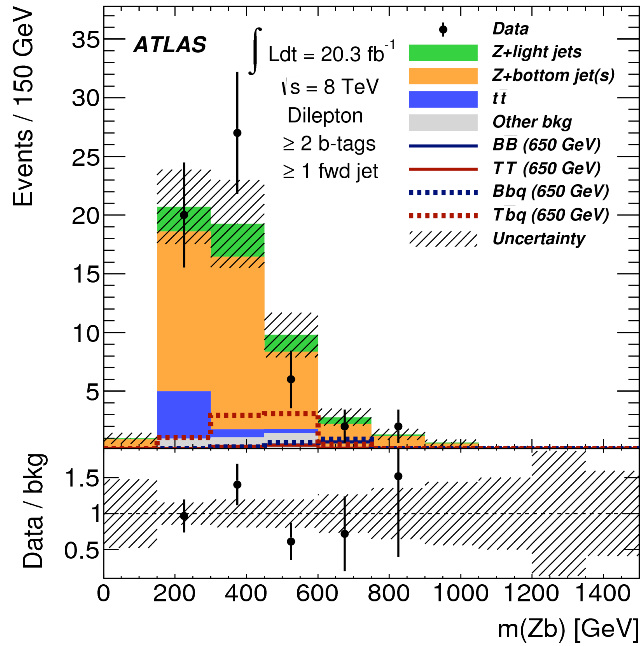
- Unfortunately - no evidence of pair production

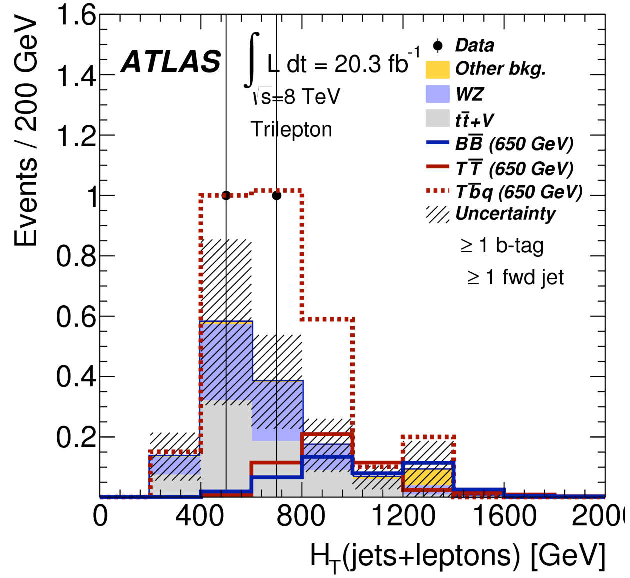




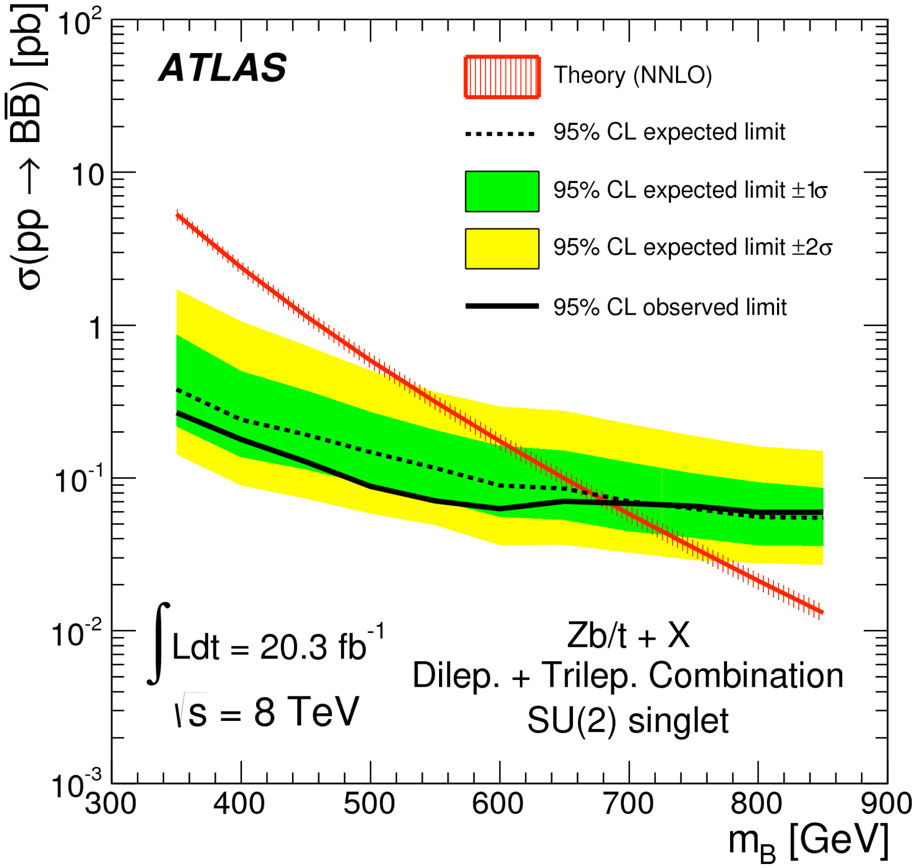
Single Production Results

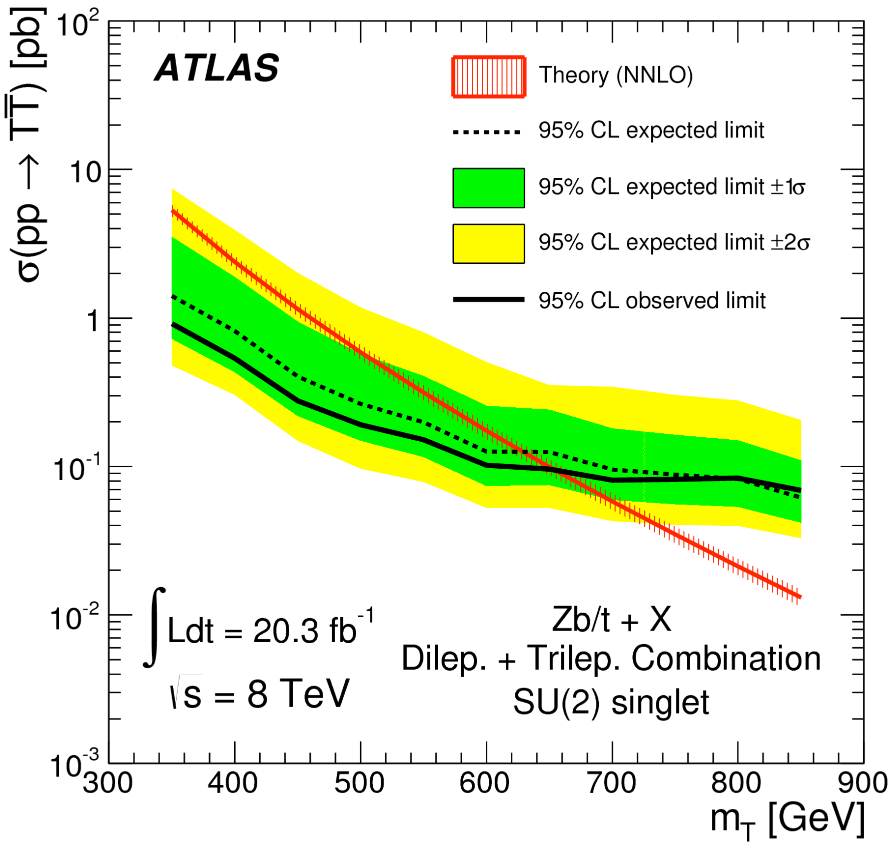
- Single production final selection also consistent with background only hypothesis
- Also proceed to set limits



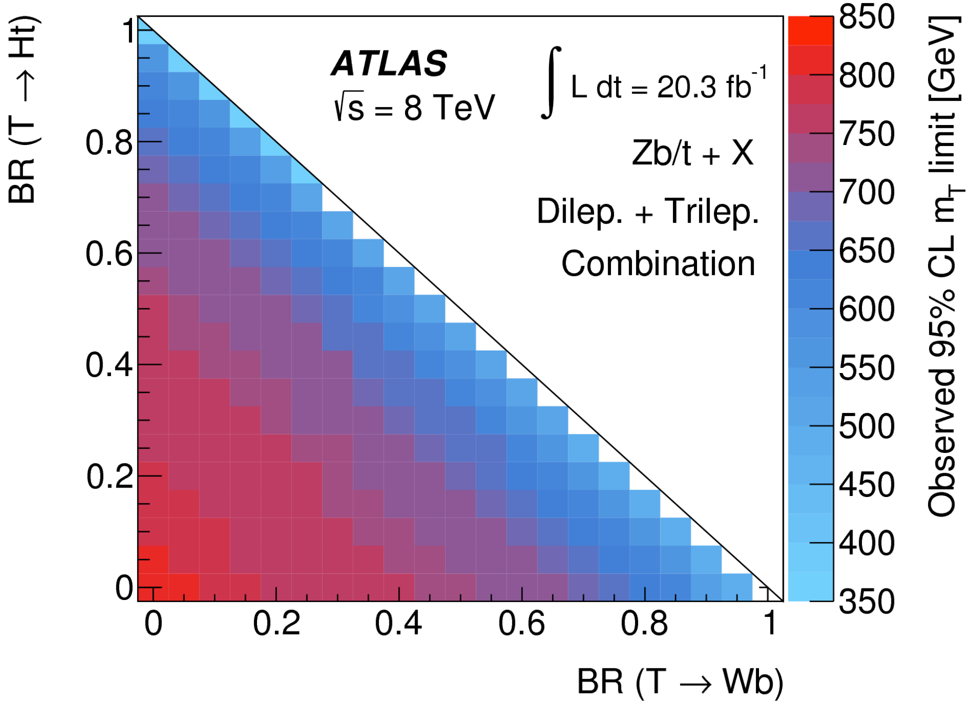


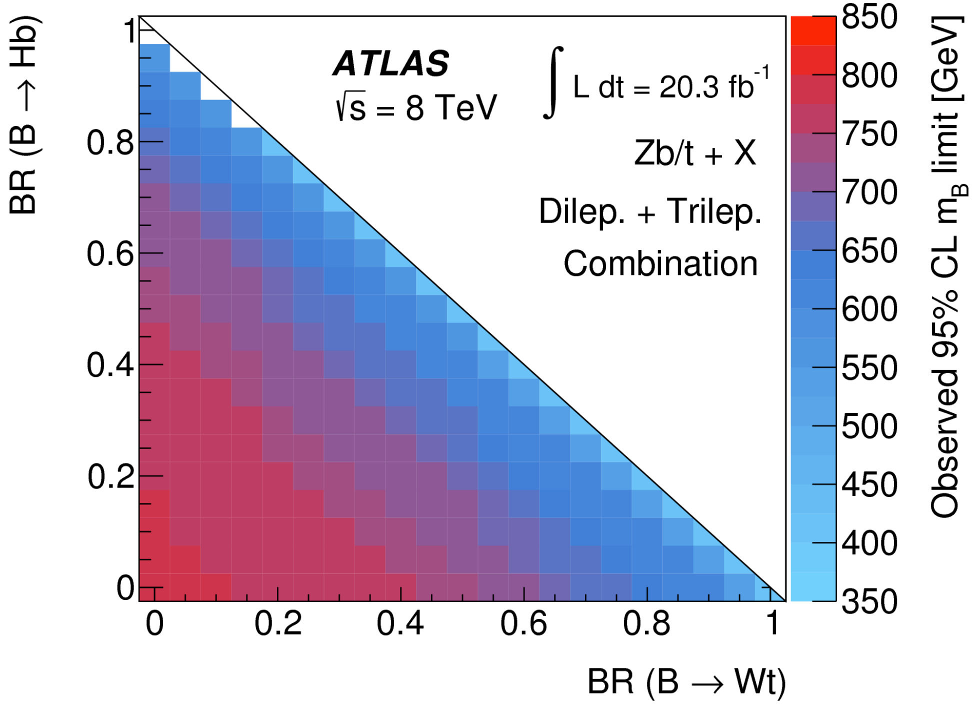
Limits,Limits, Limits



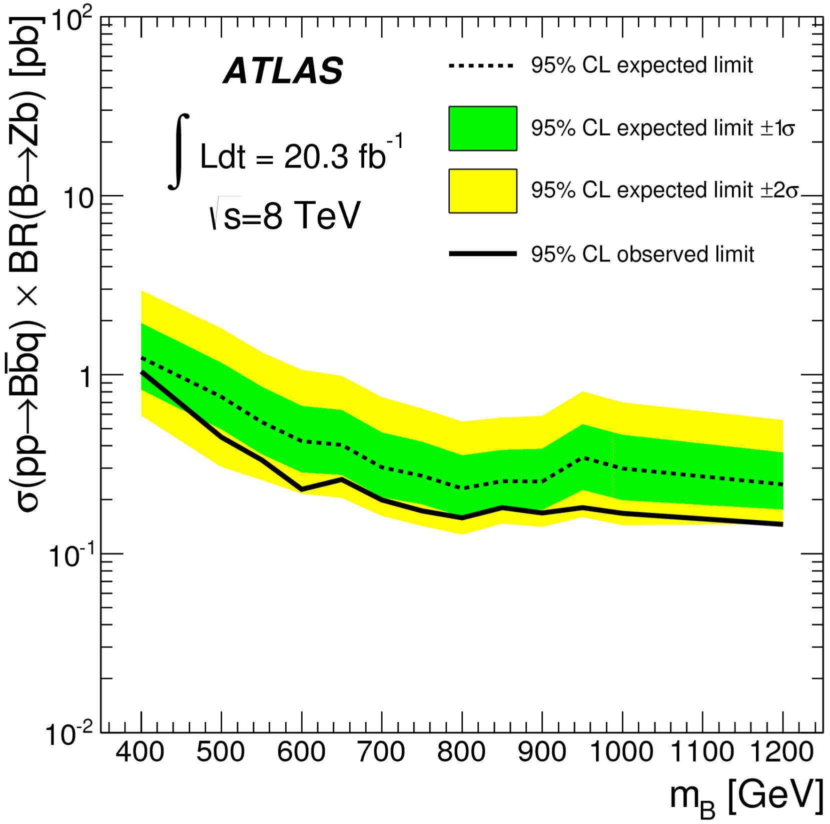


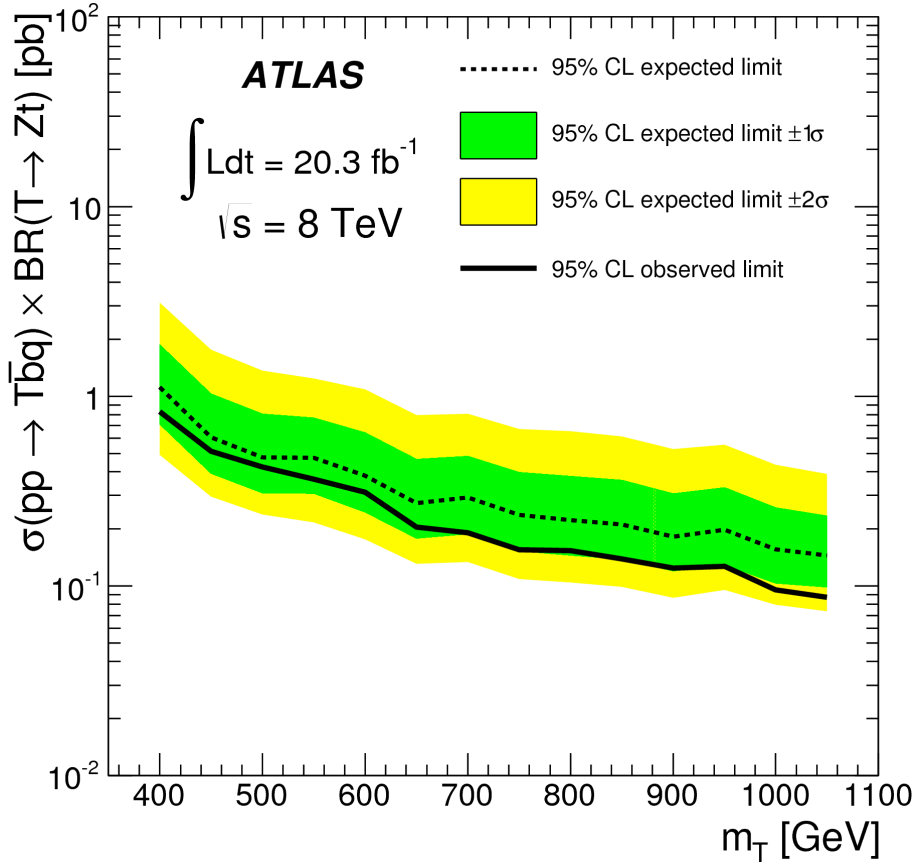
For any branching ratio



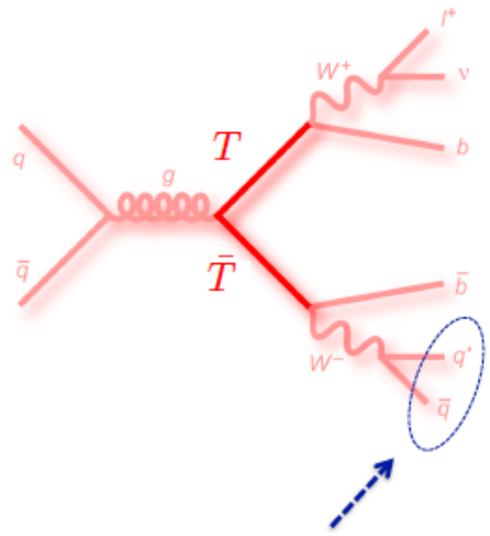


Single Production



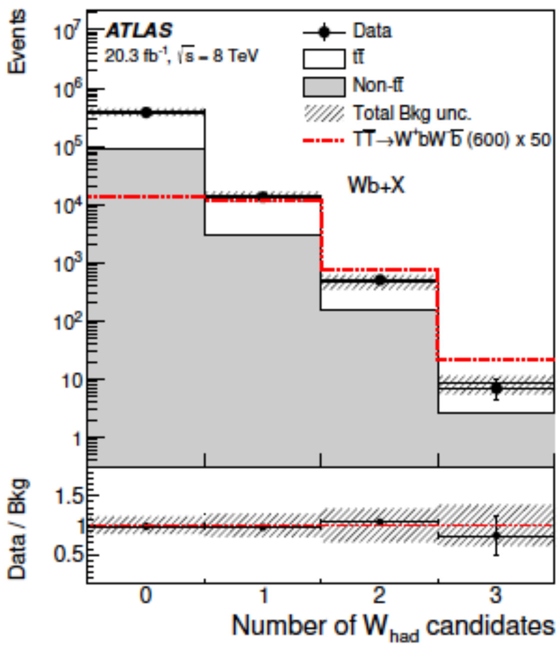


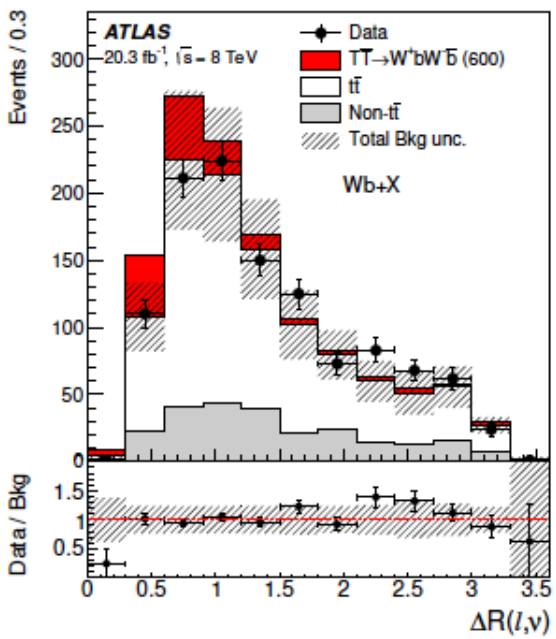
W corner of the T Plane



- Preselection: = 1 e or μ, ≥ 4 jets (R = 0.4)
- ≥ 1 b-tagged jet (70%); also label jet w/ 2nd highest b-tag weight as b-tagged. $p_T(b_{1,2}) > 160$, 80 GeV.
- $ME_T > 20$ GeV and $ME_T + M_T > 60$ GeV
- $H_T(\text{lep+jets+}ME_T) > 800$ GeV.

- Hadronic W candidate: resolved and merged types.
- Other "tight" criteria to exploit high $p_T(W)$ but wide separate between W and b-quarks in signal.

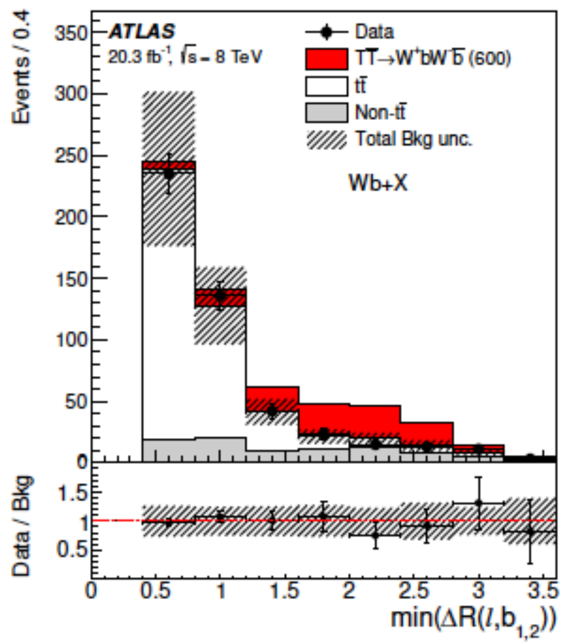




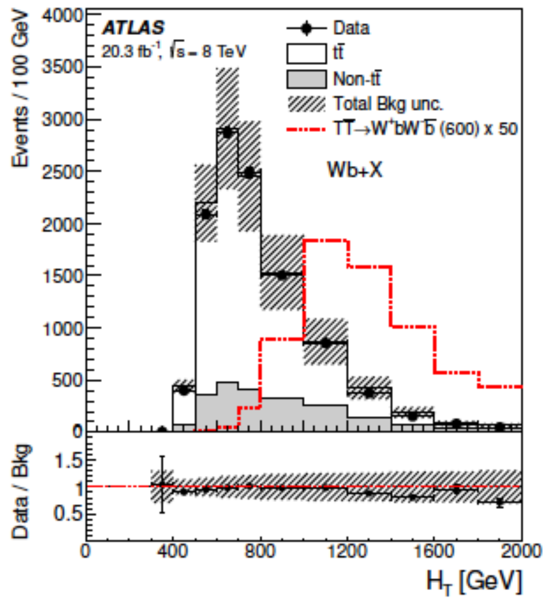
arXiv:1505.04306

W corner of T plane

Selection	Requirements
Preselection	Exactly one electron or muon $E_T^{miss} > 20$ GeV, $E_T^{miss} + m_T^W > 60$ GeV ≥ 4 jets, ≥ 1 b-tagged jets
Loose selection	Preselection ≥ 1 W_{had} candidate (type I or type II) $H_T > 800$ GeV $p_T(b_1) > 160$ GeV, $p_T(b_2) > 110$ GeV (type I) or $p_T(b_2) > 80$ GeV (type II) $\Delta R(\ell, \nu) < 0.8$ (type I) or $\Delta R(\ell, \nu) < 1.2$ (type II)
Tight selection	Loose selection $\min(\Delta R(\ell, b_{1,2})) > 1.4$, $\min(\Delta R(W_{had}, b_{1,2})) > 1.4$ $\Delta R(b_1, b_2) > 1.0$ (type I) or $\Delta R(b_1, b_2) > 0.8$ (type II) $\Delta m < 250$ GeV (type I) [see text for definition]



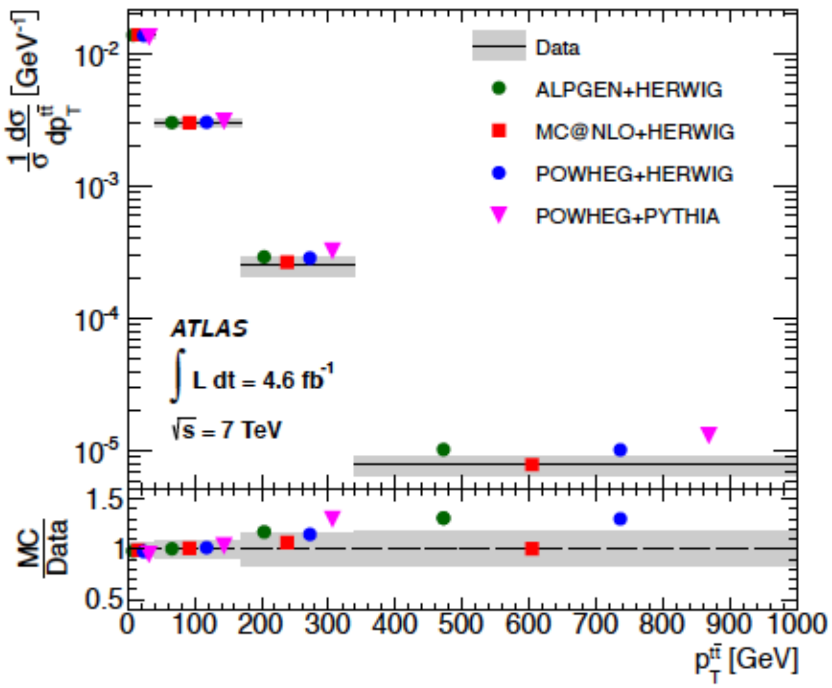
- Hadronically boosted W
  - Type 1 - single jet with P_T> 400 GeV
  - Type 2 - two jets with invariant mass 60-120 GeV, P_T> 250 GeV of dijet system $\Delta R(j, j) < 0.8$



W corner of T Plane

top pair production, differential cross section

- Main backgrounds tt+jets, W/Z+jets
    - Taken from simulation but reweighted based on top and V+jet differential cross-section measurements
- Smaller backgrounds (multijet events with misidentified lepton,diboson +jets, and tt+V)



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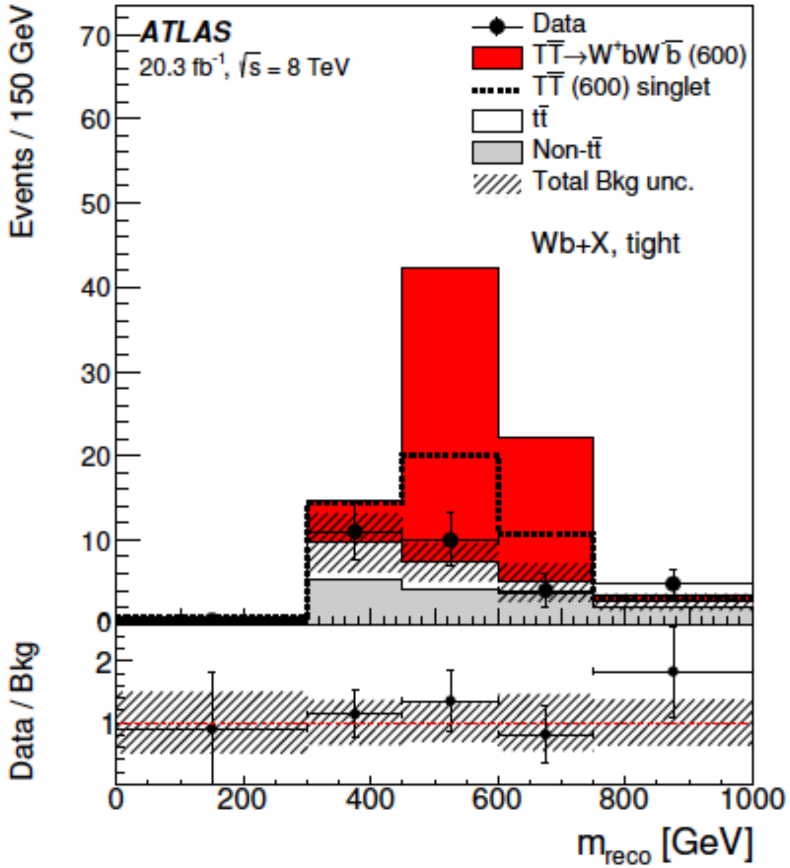
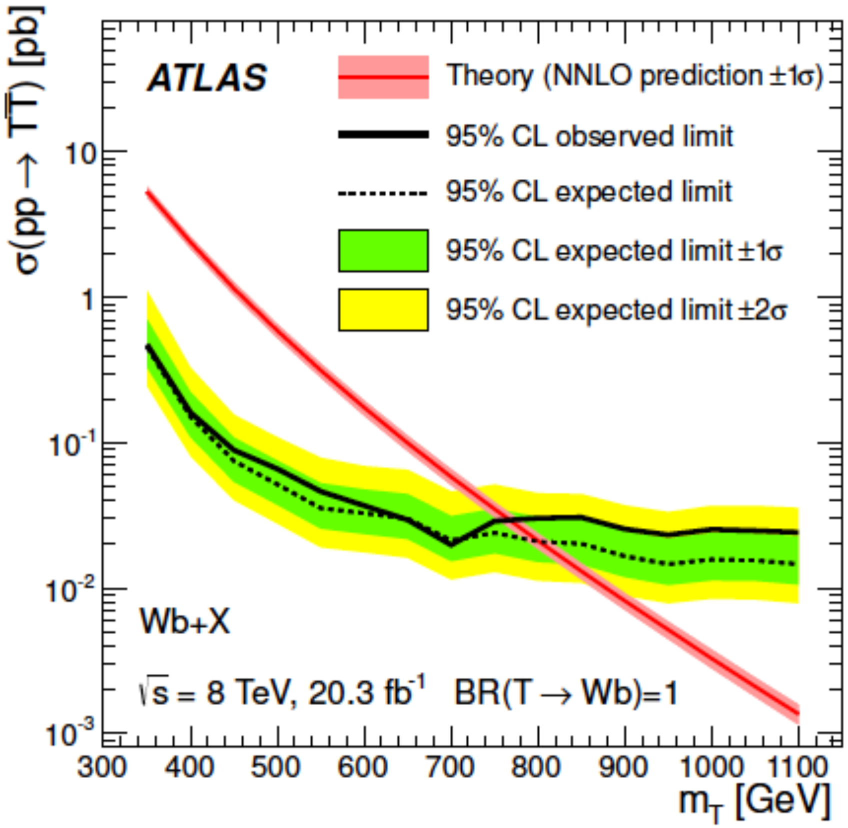
W corner of the T Plane



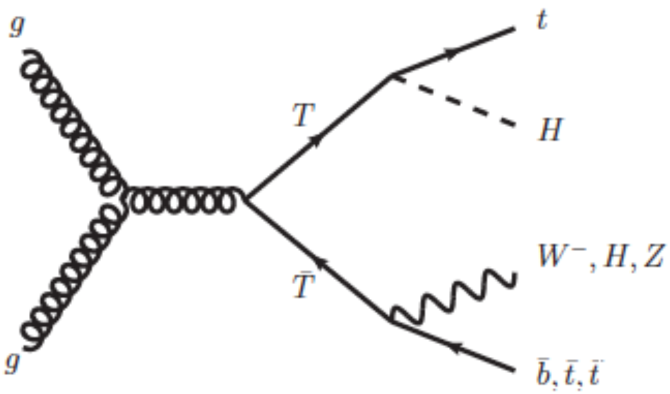


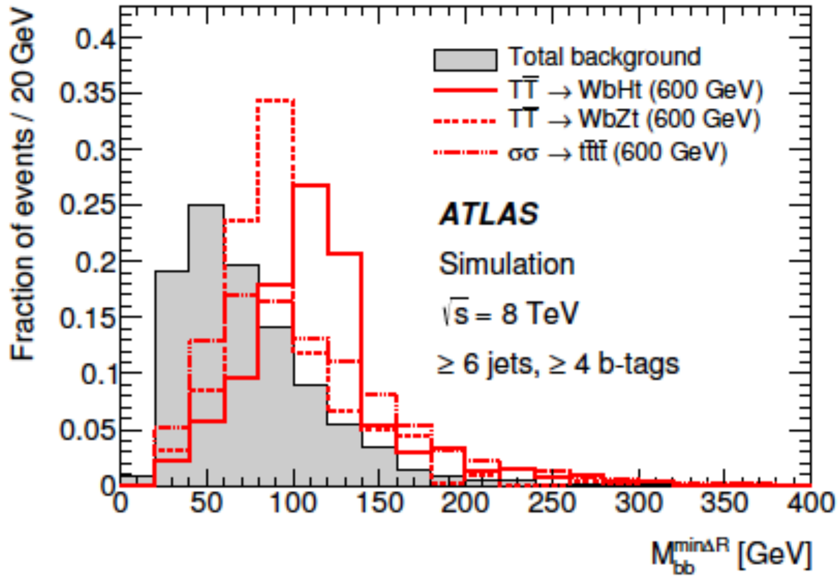
- Reconstruct WbWb system: m_{reco} formed with W_{had} and b-jet that minimizes inferred heavy quark mass difference.

- Assuming BR(Wb) = 100%, exclude m_T < 770 (795) GeV, obs (exp).
- Limits also apply to Y(-4/3) quark.

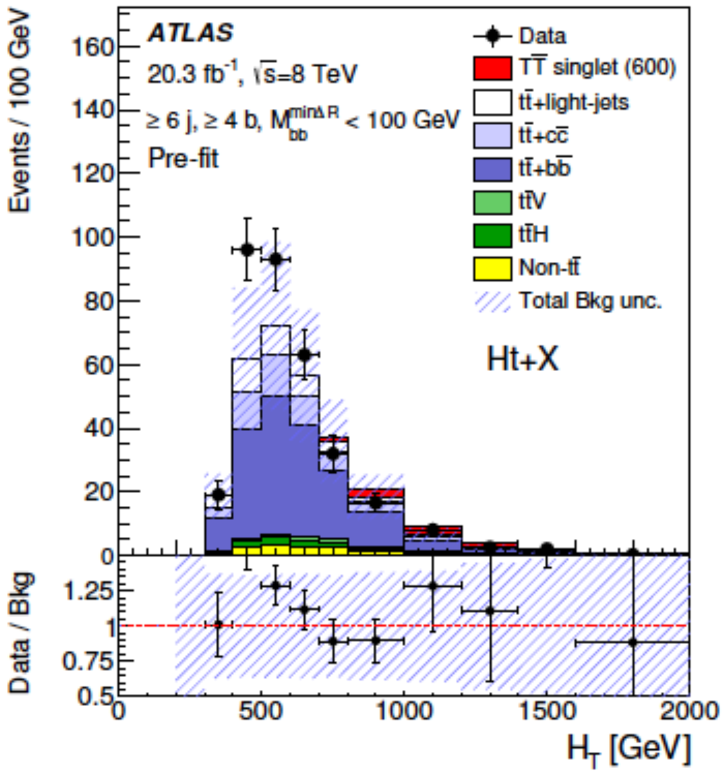
arXiv:1505.04306

H corner of the T plane





≥6 jets, ≥4 b-tags



- Targets HtHt-like final states. Complements Wb+X.
- High (5, ≥6) jet and b-jet (2, 3, ≥4) multiplicity.
- Study H_T distribution in six categories:

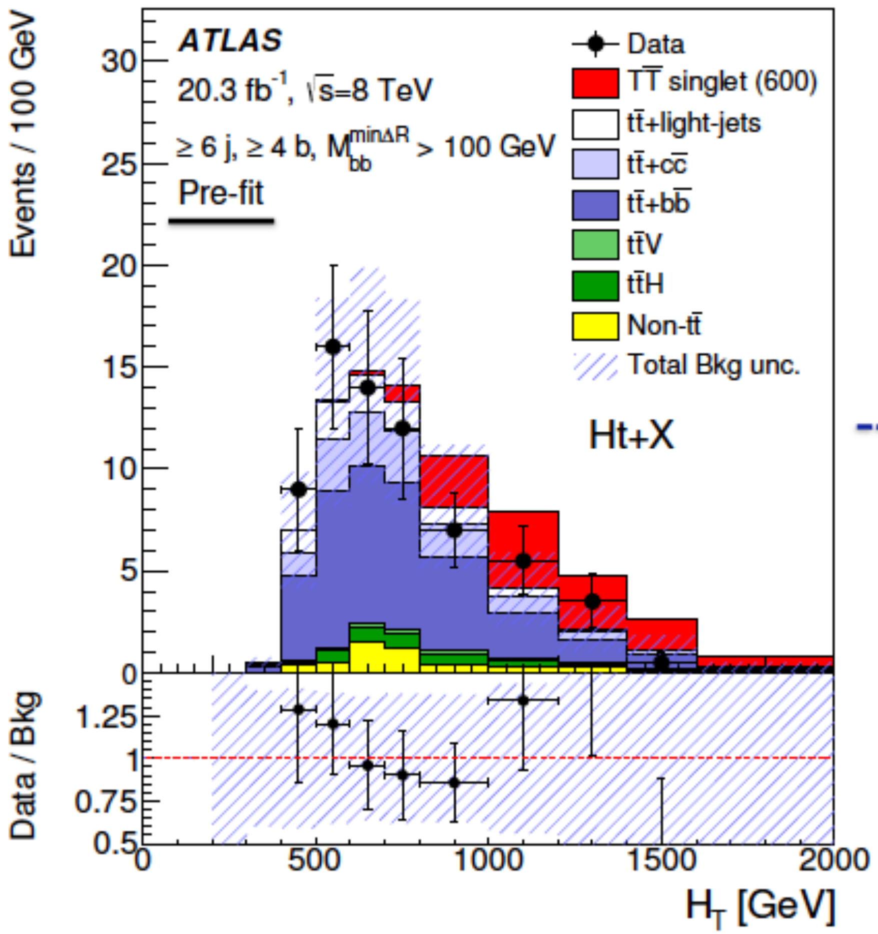
  5j2b, 5j3b, 5j4$^+$b, 6$^+$j2b, 6$^+$j3b, 6$^+$j4$^+$b
- Also, divide 4$^+$b into high and low M_{bb} (min dR pair)

arXiv:1505.04306

arXiv:1505.04306

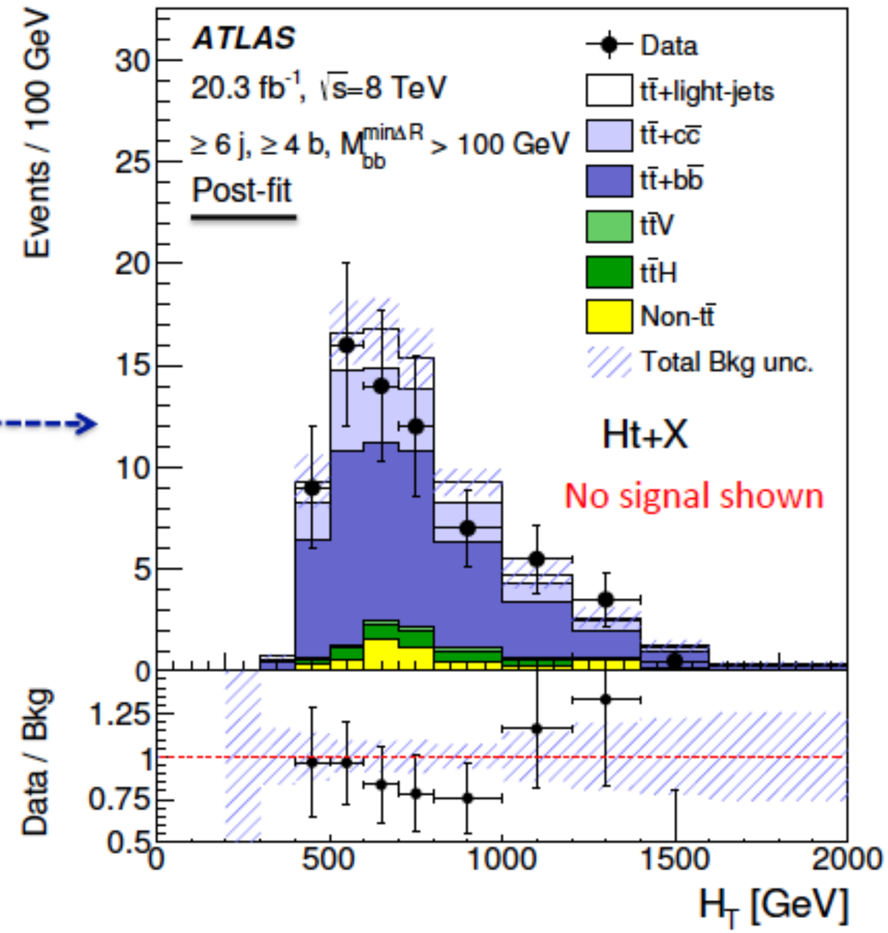
H corner of T Plane

- Low S/B categories used to constrain uncertainties (e.g. JES, b-tagging, tt+HF norms)



Data: 84

BG (prefit): 81 ± 30



Data: 84

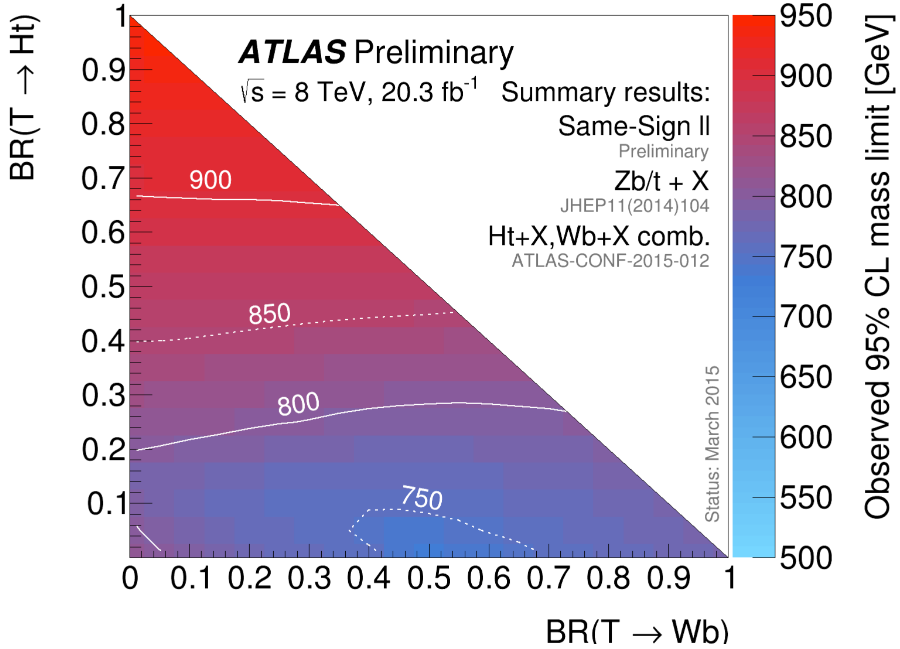
BG (postfit): 94 ± 5

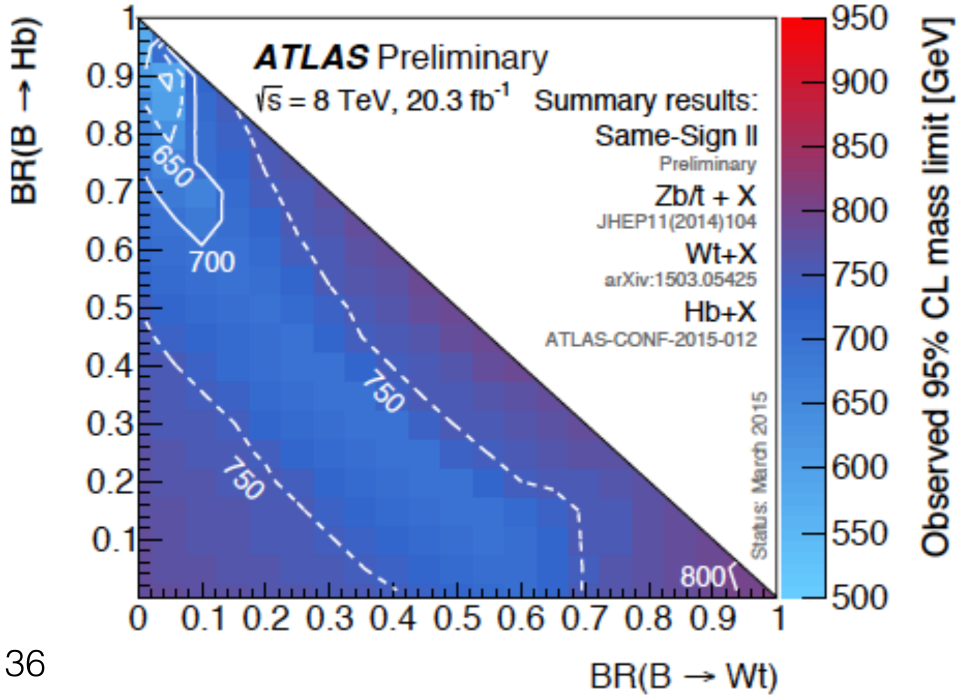
Combined Limits

- Each analysis designed for somewhat different corner of phase space

- Combine limits across the branching ratio plane in both T and B decay hypothesis

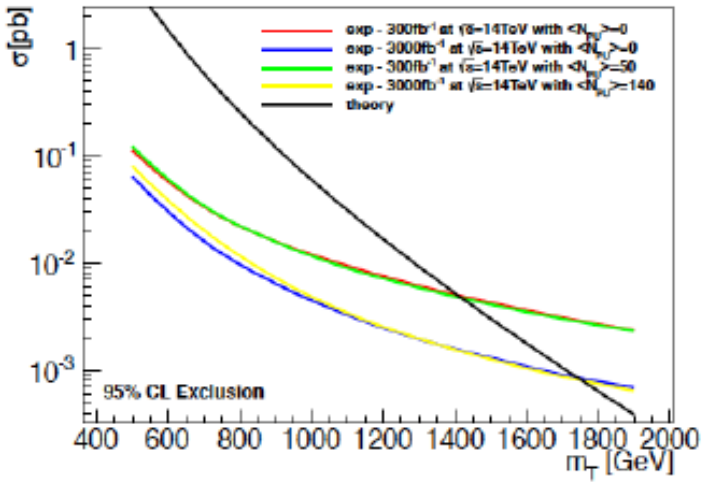
- Observation slightly better than expected limits

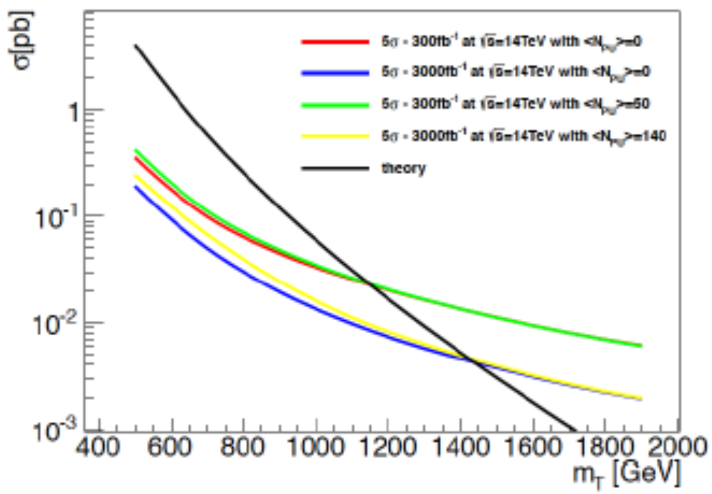




Projections for Run II and beyond

Collider	Luminosity	Pileup	3σ evidence	5σ discovery	95% CL
top-partner pair production					
LHC 14 TeV	300 fb^{-1}	50	1340 GeV	1200 GeV	1450 GeV
LHC 14 TeV	3 ab^{-1}	140	1580 GeV	1450 GeV	1740 GeV
LHC 33 TeV	3 ab^{-1}	140	2750 GeV	2400 GeV	3200 GeV
top-partner single production					
LHC 14 TeV	300 fb^{-1}	50	1275 GeV	1150 GeV	
LHC 14 TeV	3 ab^{-1}	140	1130 GeV	1000 GeV	
LHC 33 TeV	3 ab^{-1}	140	1350 GeV	1220 GeV	
bottom-partner pair production					
LHC 14 TeV	300 fb^{-1}	50	1210 GeV	1080 GeV	1330 GeV
LHC 14 TeV	3 ab^{-1}	140	1490 GeV	1330 GeV	>1500 GeV
LHC 33 TeV	300 fb^{-1}	50	> 1500 GeV	> 1500 GeV	> 1500 GeV
Charge 5/3 fermion pair production					
LHC 14 TeV	300 fb^{-1}	50	1.51 TeV	1.39 TeV	1.57 TeV
LHC 14 TeV	3 ab^{-1}	140	1.66 TeV	1.55 TeV	1.76 TeV
LHC 33 TeV	3 ab^{-1}	140	2.50 TeV	2.35 TeV	2.69 TeV





- Note these are SNOWMASS projections (not ATLAS results)

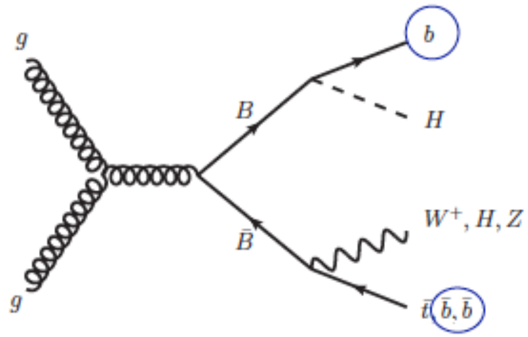
arXiv:1311.0299

Conclusions

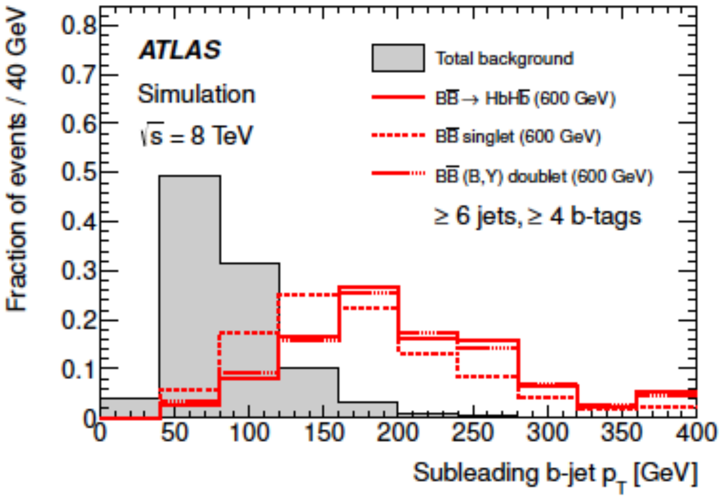
- Large program to search for vector like quark in different final states under different production and decay hypothesis
- No Evidence for VLQ production at ATLAS
- Early Search Topic as increase in energy should quickly surpass run I sensitivity
- Check Run I excesses - try to remain as broad as possible
- Ultimate Run II sensitivity ~ 2 TeV

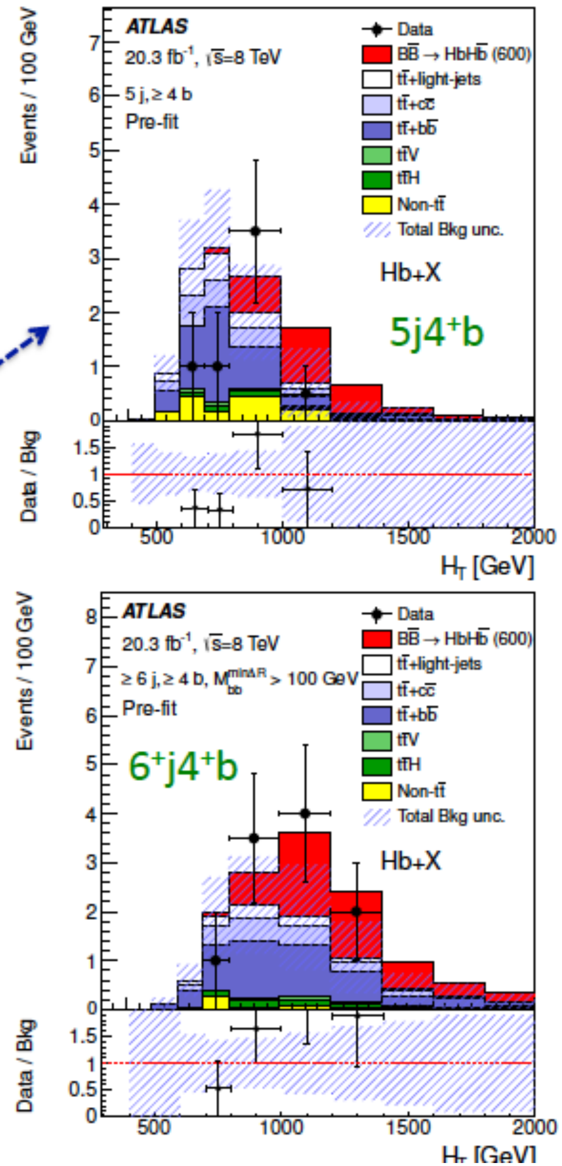
H corner of B plane

- Re-optimize Ht+X analysis for the B plane.



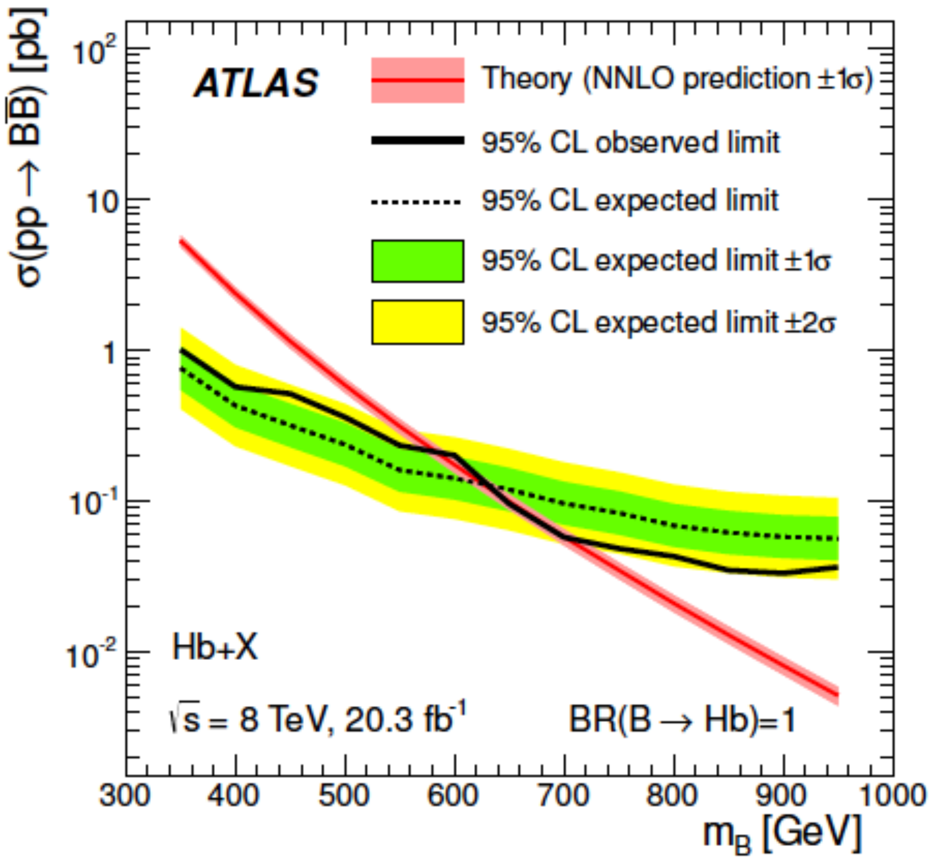
- Require p_T of leading two b-jets > 150 GeV.
- Increased importance of 5 jet category compared to the T hypothesis case.

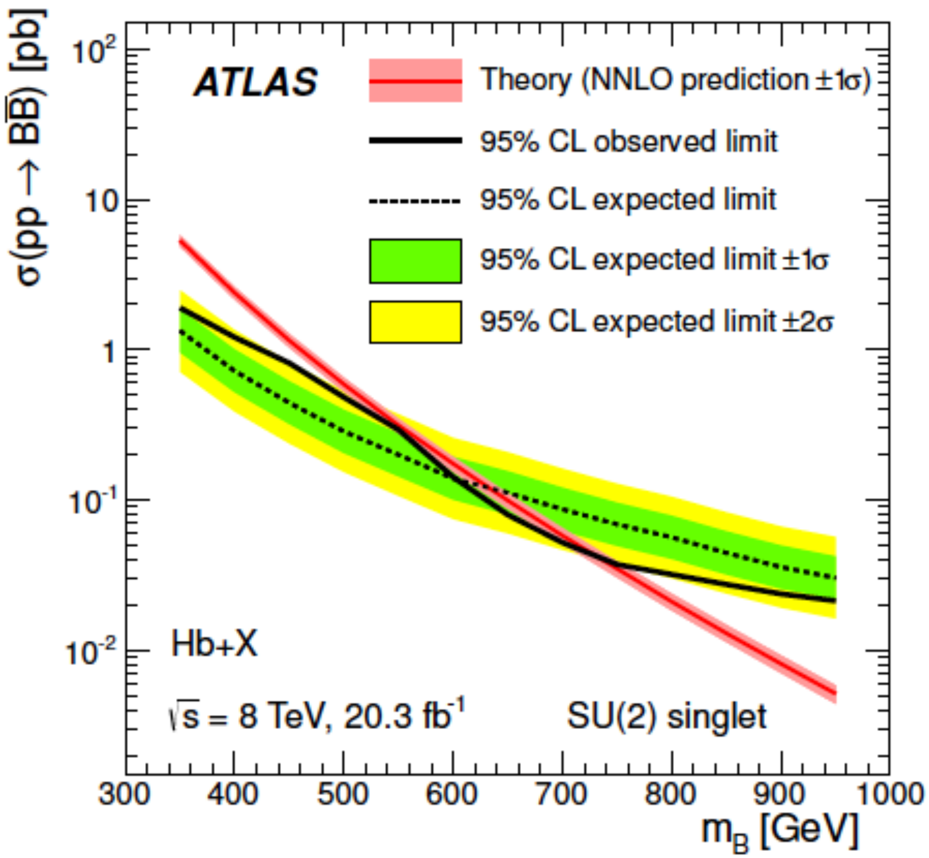




H corner of B Plane

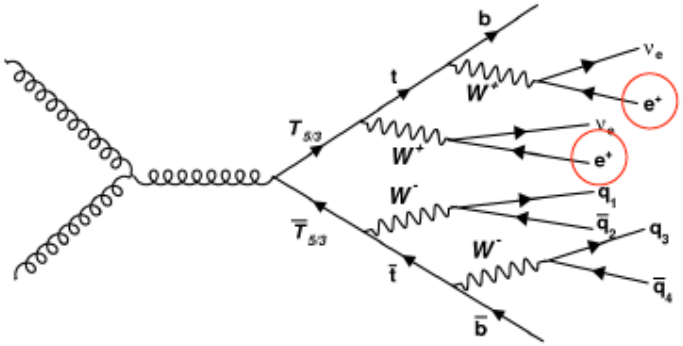
- Exclusions for 100% Hb and SU(2) singlet hypotheses.



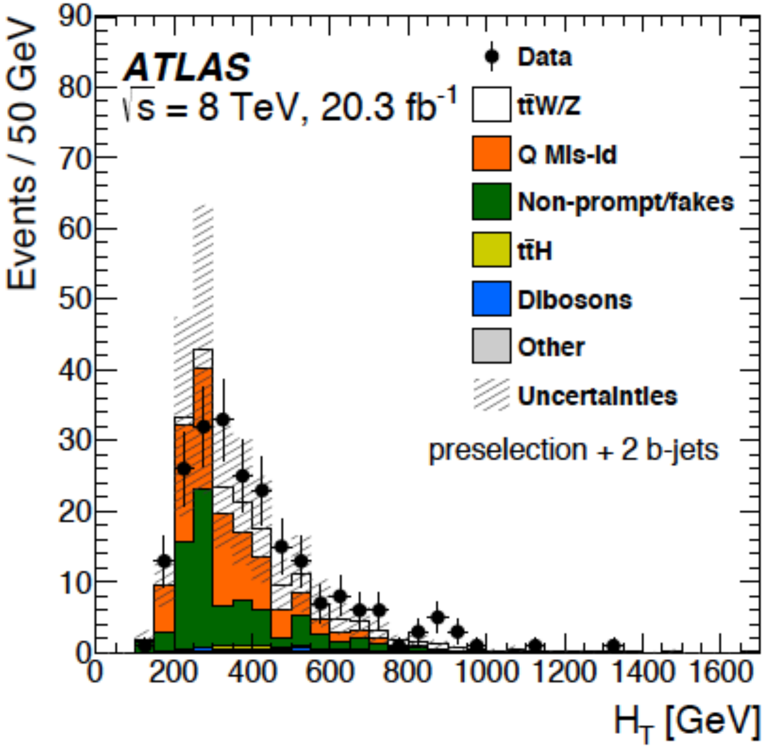


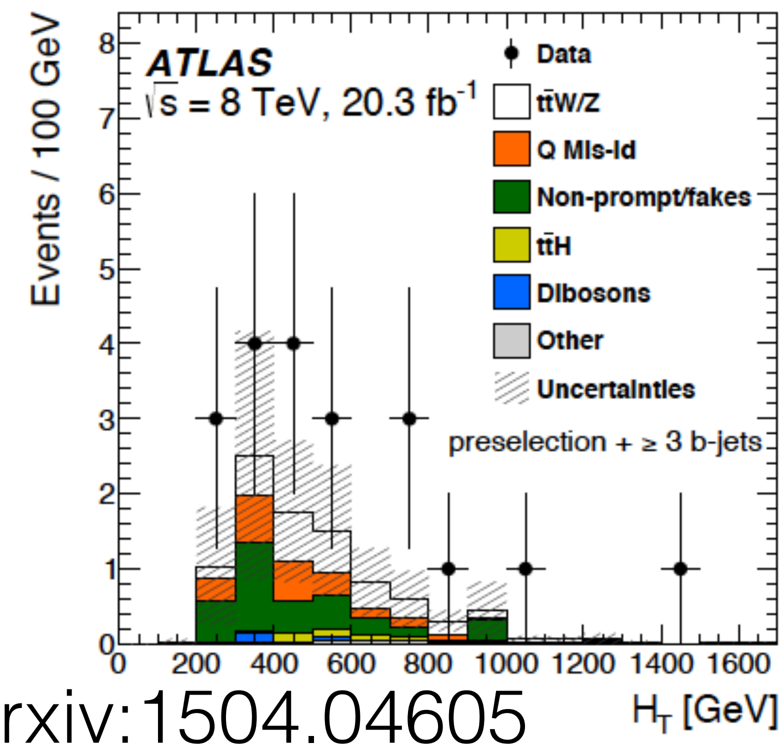
- For BR(Hb) = 100%, exclude $m_B < 700$ (625) GeV, obs (exp).
- For BR(Hb) ≈ BR(Zb) ≈ 25%, exclude $m_B < 735$ (635) GeV, obs (exp).

Same Sign Signature



- Same-sign dilepton final state originally motivated by 4W signature from BB & XX.
- Later added 3rd lepton channel, and interpreted also for TT.
- Challenges: fake leptons and Q mis-Id.

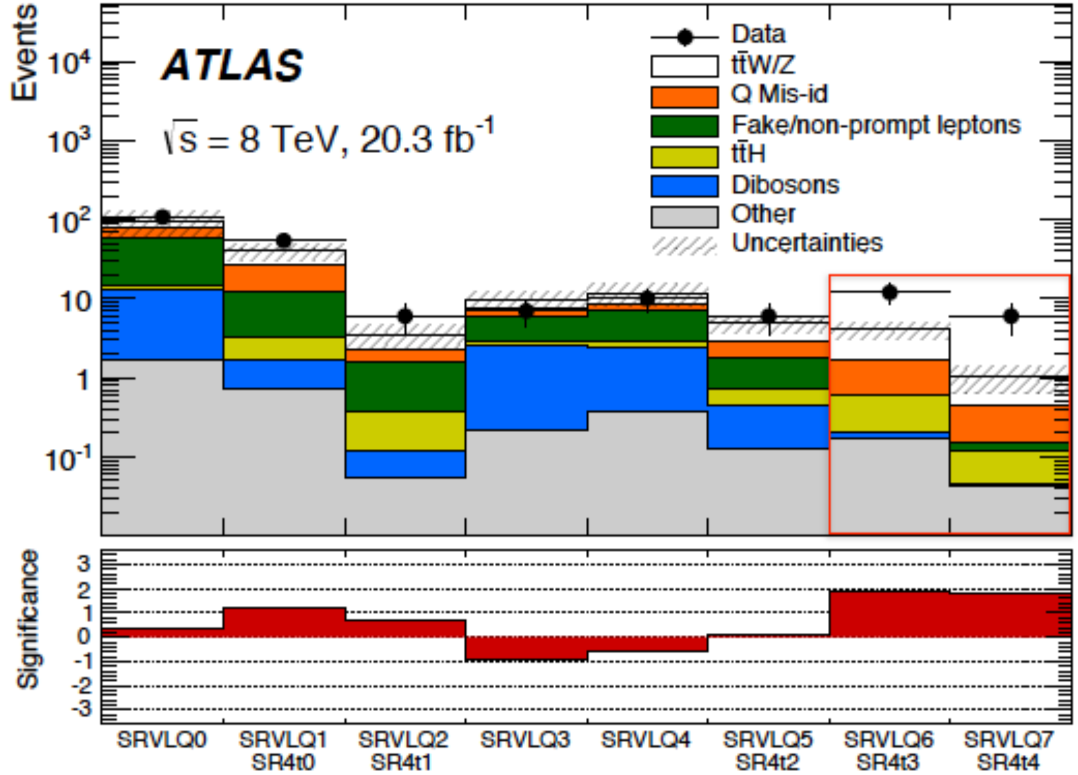




arxiv:1504.04605

arxiv:1504.04605

Definitions of event categories (signal regions)

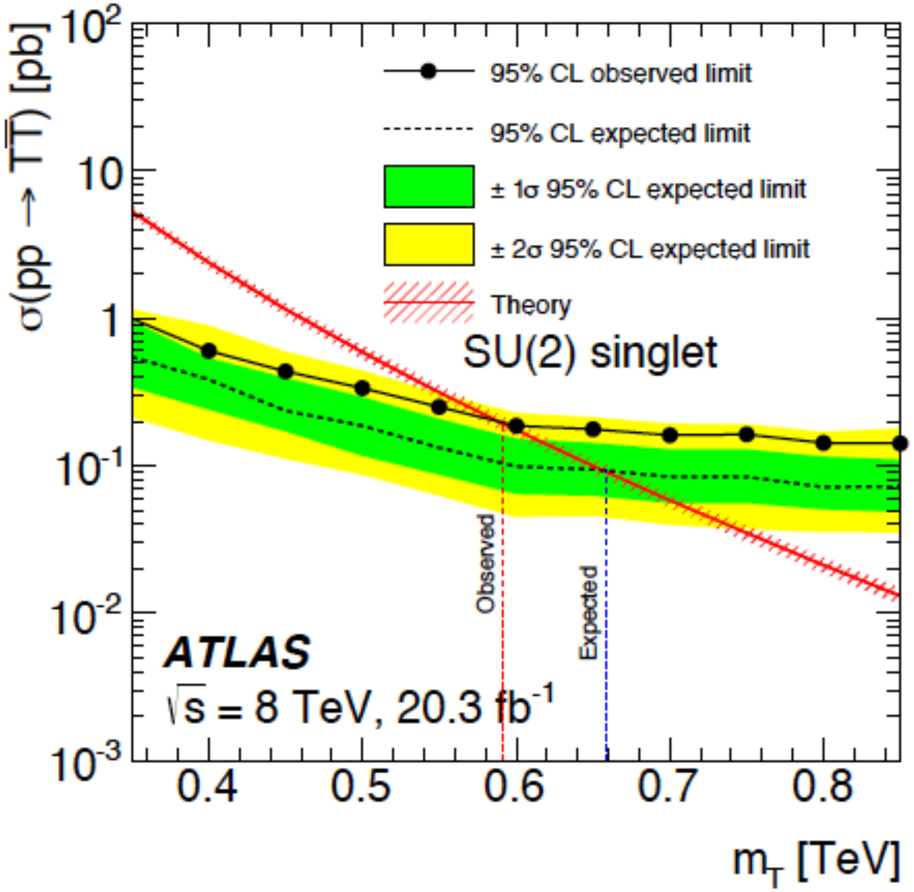


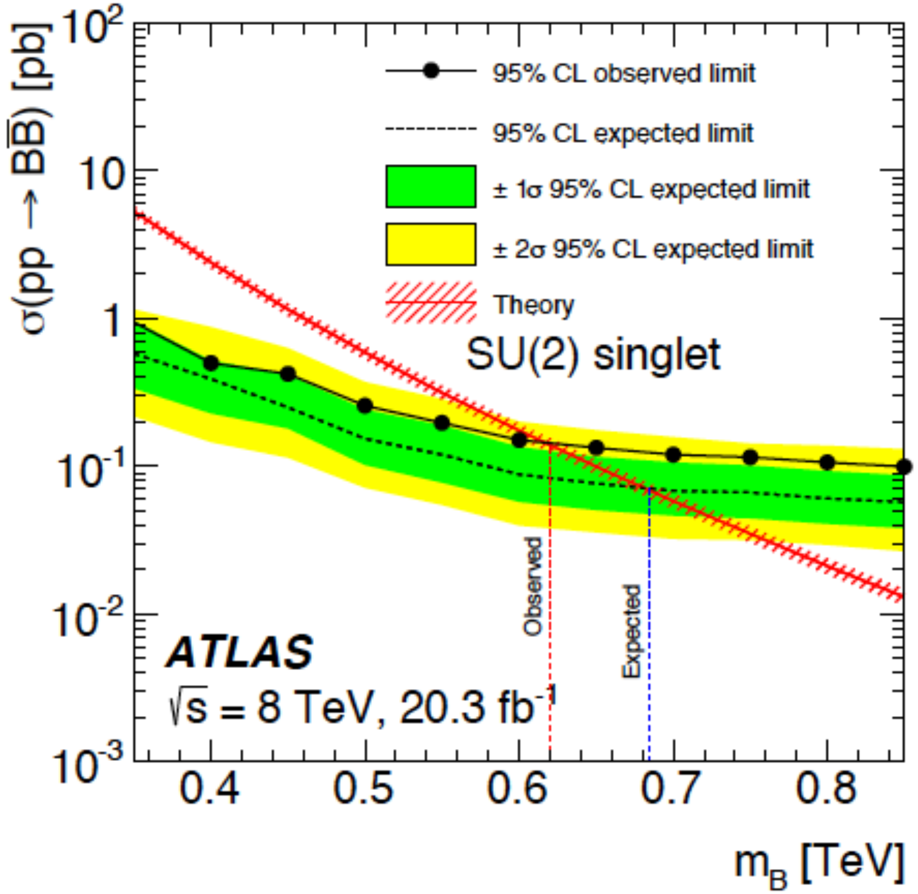
SRVLQ6:
Exp: 4.3 ± 1.5
Obs: 12

SRVLQ7:
Exp: 1.1 ± 1.0
Obs: 6

Definition			Name	
$e^{\pm}e^{\pm} + e^{\pm}\mu^{\pm} + \mu^{\pm}\mu^{\pm} + eee + ee\mu + e\mu\mu + \mu\mu\mu,\ N_j \geq 2$				
$400 < H_T < 700GeV$	$N_b = 1$	$E_T^{miss} > 40$ GeV	SRVLQ0	
	$N_b = 2$		SRVLQ1	SR4t0
	$N_b \geq 3$		SRVLQ2	SR4t1
$H_T \geq 700$ GeV	$N_b = 1$	$40 < E_T^{miss} < 100GeV$	SRVLQ3	
		$E_T^{miss} \geq 100$ GeV	SRVLQ4	
	$N_b = 2$	$40 < E_T^{miss} < 100GeV$	SRVLQ5	SR4t2
		$E_T^{miss} \geq 100$ GeV	SRVLQ6	SR4t3
	$N_b \geq 3$	$E_T^{miss} > 40$ GeV	SRVLQ7	SR4t4

- Exclusions for SU(2) singlet T and B hypotheses.





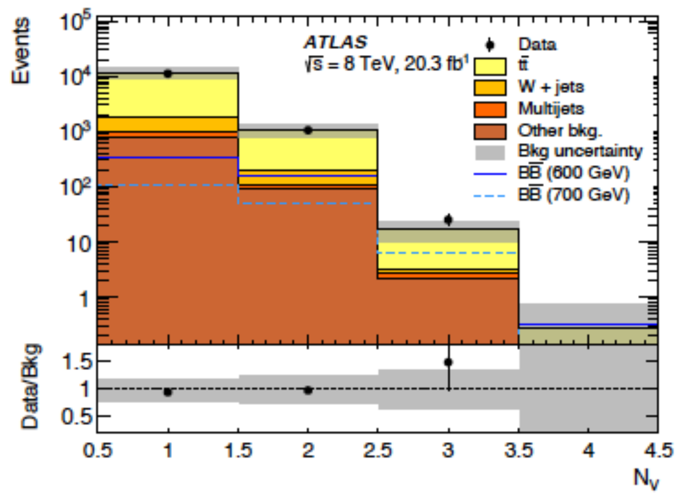
- For BR(Ht) ≈ BR(Zt) ≈ 25%, exclude m_T < 620 (660) GeV, obs (exp).
- For BR(Hb) ≈ BR(Zb) ≈ 25%, exclude m_B < 590 (690) GeV, obs (exp).

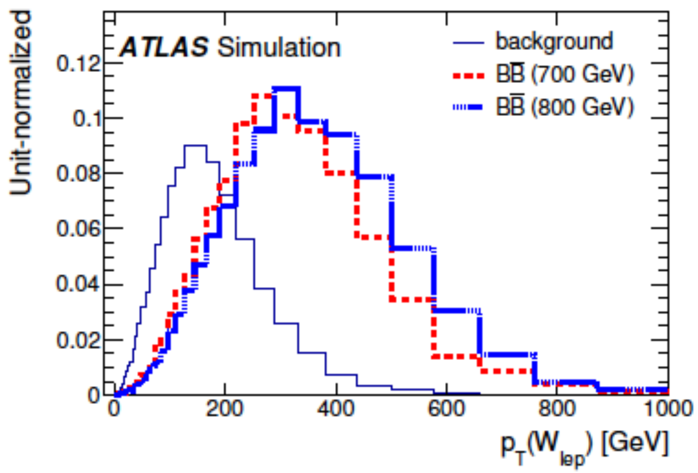
arxiv:1504.04605

W corner of B plane

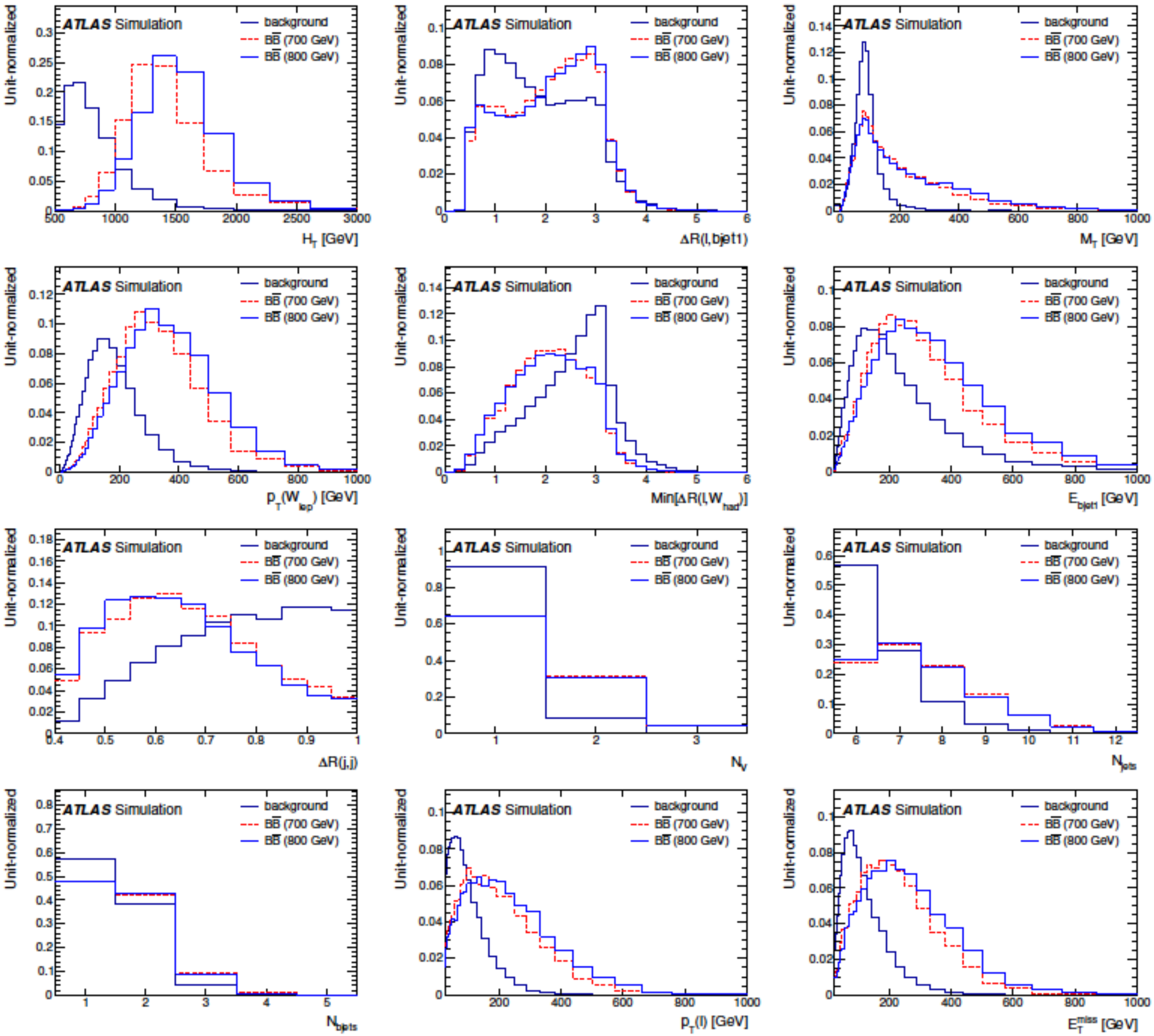
$$pp \to X\bar{X} \to tW^+\bar{t}W^- \to W^+W^+W^-W^-b\bar{b}$$

- Examine also higher background channels
- Also check the one lepton channel in the VLQ interpretation of the 2.5 sigma excess
- 12 variable BDT trained to maximize sensitivity



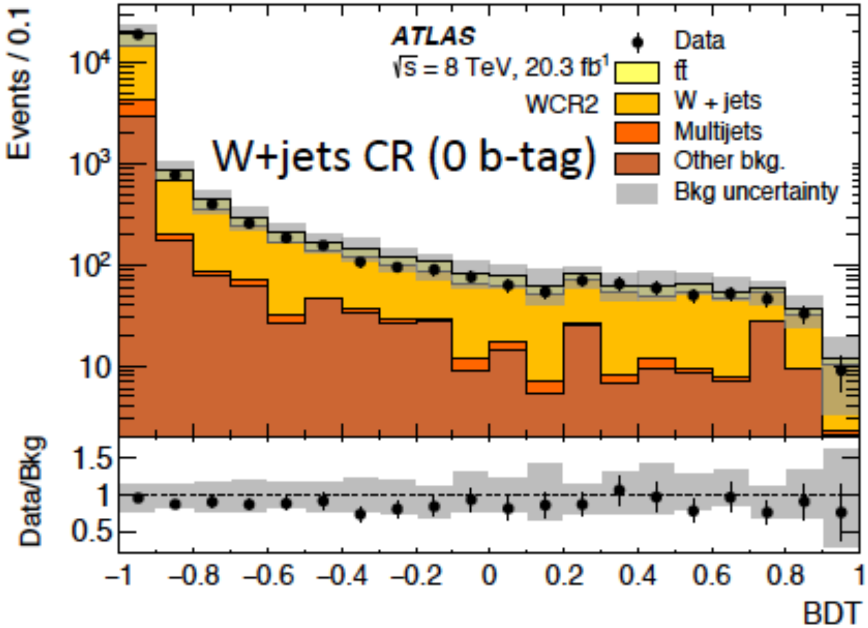


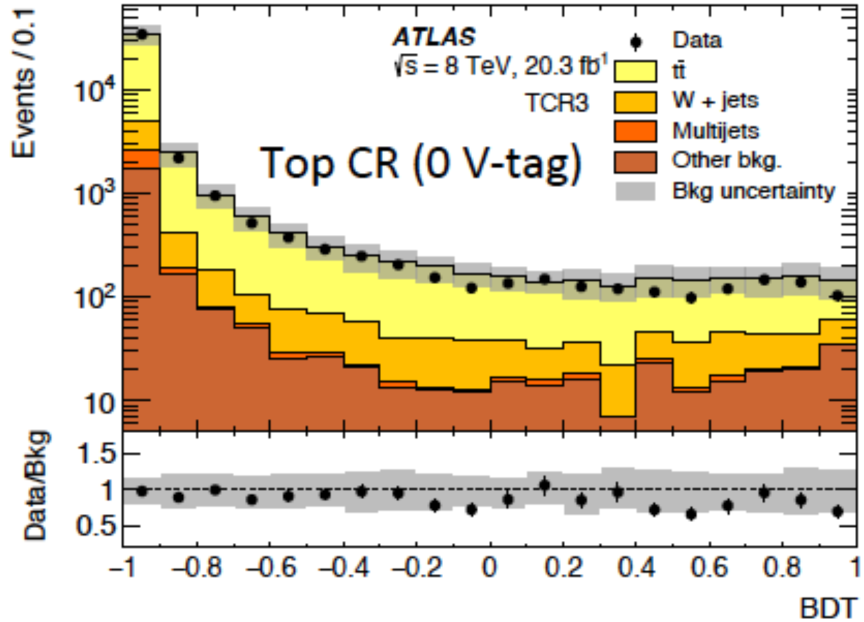
arXiv:1505.04306

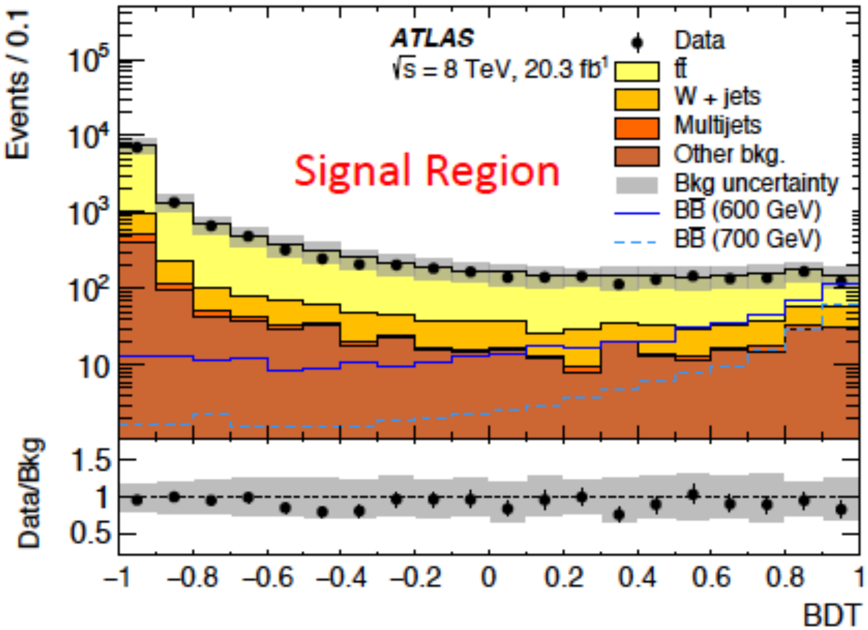


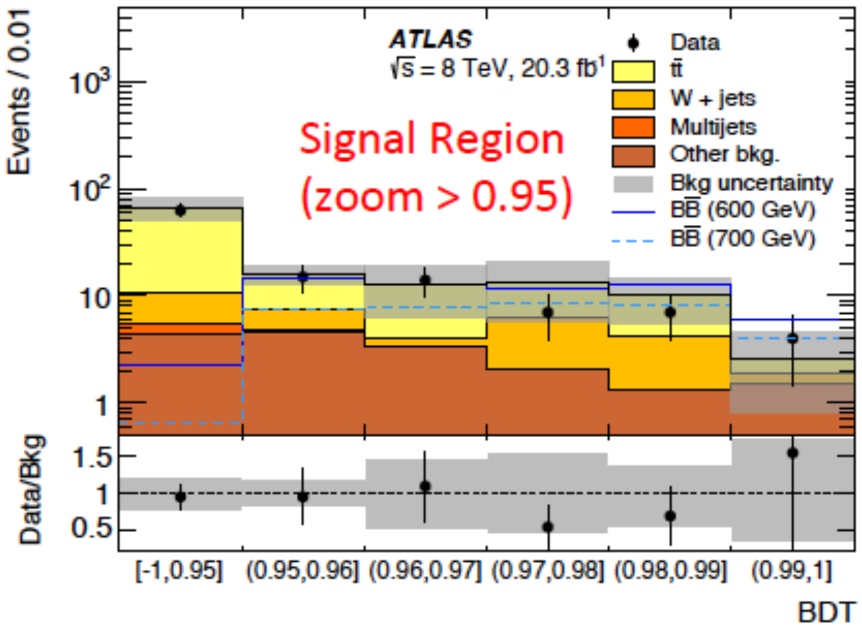
 arXiv:1505.04306

BDT performance



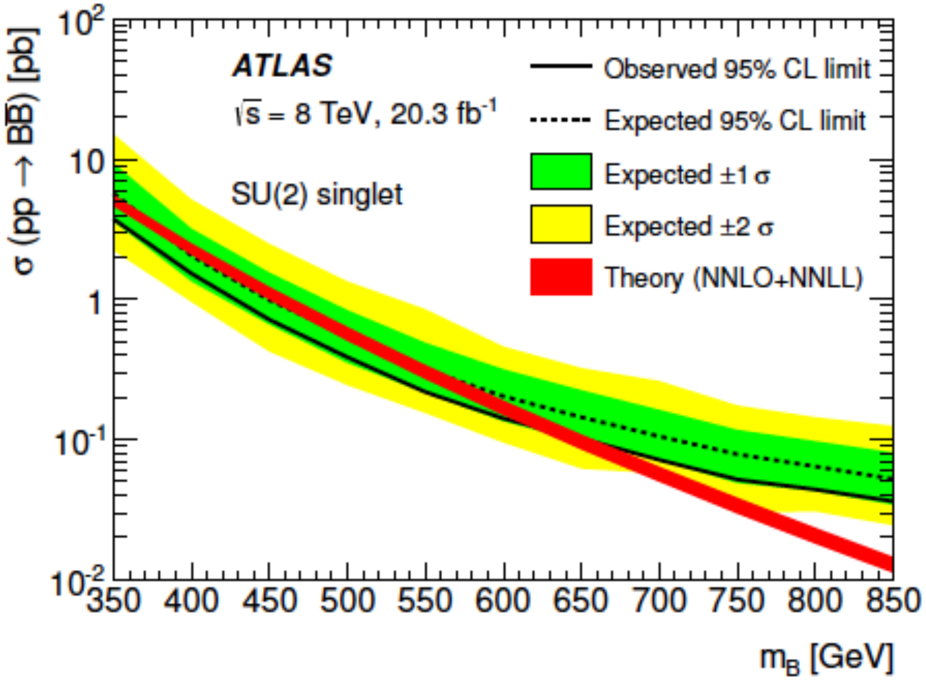


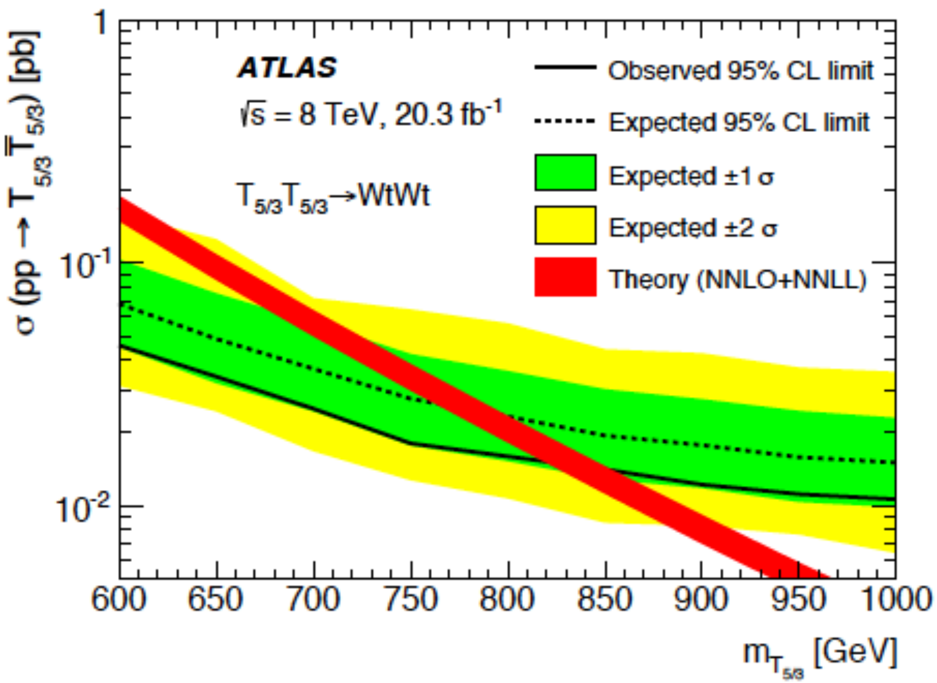




arXiv:1505.04306

Limits from B->TW Search single lepton



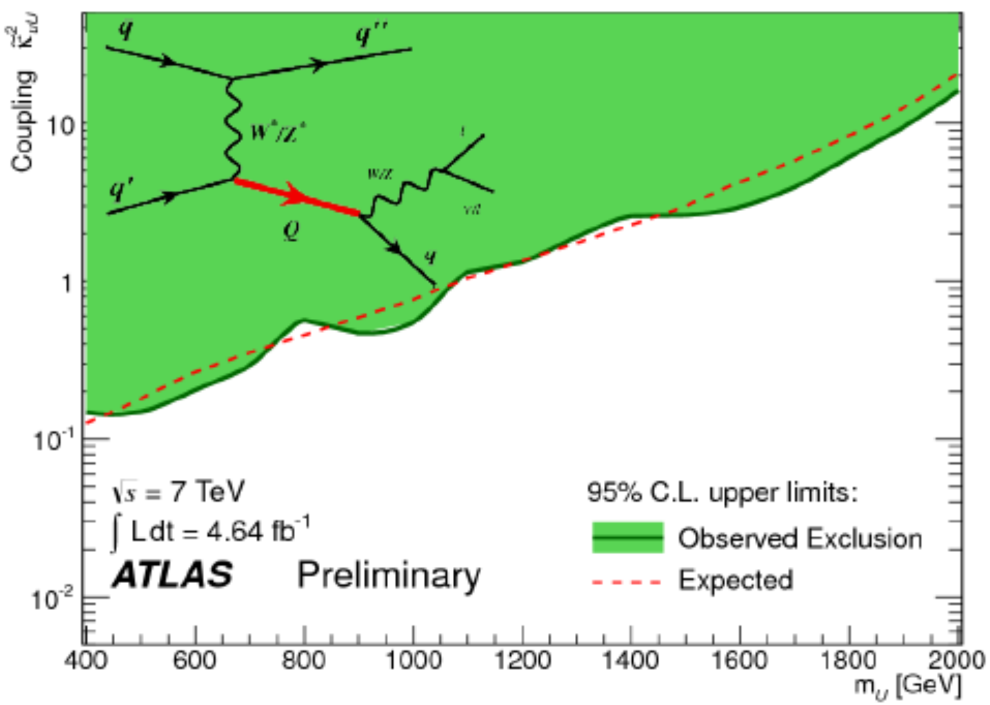


- For BR(Hb) ≈ BR(Zb) ≈ 25%, exclude m_T < 640 (505) GeV, obs (exp).
- For BR(Wt)=100%, exclude m_X < 840 (780) GeV, obs (exp).

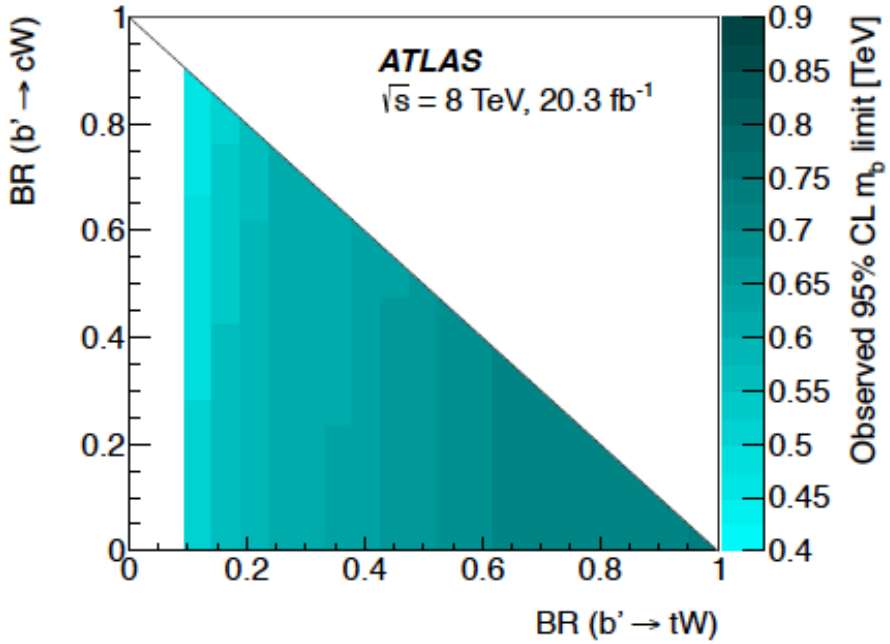
arXiv:1505.04306

Coupling to Light Quarks?

- VLQ coupling to light generations: single production from valence quarks.
- Search for Wq and Zq resonances.



ATLAS-CONF-2012-137 [7 TeV, 4.6/fb]
PLB 712 (2012) 22 [7 TeV, 1.0/fb]



- SS+ 1 b-jet signature still possible w/ BR(cW) ≠ 0.